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Flood forecasting using HEC-HMS model for Sukkur district, Pakistan

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Abstract

This study investigates the applicability of the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) for reliable flood forecasting in the Sukkur District, Pakistan, a lower Indus Basin region that suffers on average three major flood events per decade and experienced catastrophic inundation of over 1,200 km^2 of cropland during the 2022 monsoon. We delineated the 5,165 km^2 Sukkur watershed into eight sub-basins using a 30 m SRTM-derived DEM and applied HEC-HMS with locally calibrated parameters—initial and constant loss, SCS unit hydrograph, and constant monthly baseflow—driven by daily rainfall (2018–2022) from Guddu, Sukkur and Kotri stations and six-hourly discharge at the Sukkur gauge. Representing the first calibrated HEC-HMS application with an eight-subbasin configuration in the region, this approach provides improved spatial resolution over lumped models. Calibration on three flood peaks (July 2020, August 2021, August 2022) and validation against an independent September 2022 event yielded a Nash-Sutcliffe Efficiency of 0.92 and a Root Mean Square Error of 55 m^3/s, while the model provided an 18-hour lead time for peak discharge forecasts. These results demonstrate HEC-HMS's strong potential as an operational early-warning tool to enhance emergency preparedness and minimize flood impacts in Sukkur and underscore the value of integrating real-time telemetry networks, coupling with two-dimensional hydraulic models, and conducting comprehensive sensitivity analyses to further improve forecast accuracy and support decision-making.

Keywords: Flood forecasting, Flood risk assessment, HEC-HMS, Hydrological modeling, Early warnings systems, Rainfall-runoff modeling

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Contents

Contribution of this paper to the literature
This study is the first to calibrate HEC-HMS across four years of Sukkur hydrometeorological data using an eight-subbasin configuration, achieving an 18-hour forecast lead time (NSE = 0.92). It also outlines real-time telemetry integration and 2D hydraulic coupling to advance operational early-warning systems.

1. Introduction

1.1. Context and Background

The Sukkur District in Pakistan frequently experiences severe floods, significantly impacting lives, agriculture, and infrastructure, vividly highlighted by the catastrophic 2022 floods. The rate, regularity, magnitude, and likelihood of disasters have been increasing in the past few decades [1]. Floods are catastrophic both in terms of loss of human life and finances. Pakistan has a history of frequent and repeated flooding [2]. Ninety percent of Pakistan's population is affected by hazards and disasters, and it suffers from floods alone [3]. Geographically, Pakistan can be divided into three major sections - mountains in the north, plateau in the southwest (Balochistan) and the Indus River plain in the middle [4].

Flooding remains one of the most destructive natural hazards affecting Pakistan, with significant impacts on infrastructure, agriculture, and communities, especially in regions along the Indus River Ali [5]. Given these challenges, accurate and timely flood forecasting has become essential to disaster risk reduction efforts, enabling authorities to plan effective responses and mitigate potential damages [6].

Despite many studies utilizing various hydrological models for flood prediction, there remains a critical gap regarding locally calibrated flood models specifically for Sukkur. This gap limits the accuracy and applicability of predictions for effective disaster management in the region. Therefore, this study aims to evaluate the effectiveness and accuracy of the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) in forecasting floods in Sukkur using locally calibrated parameters. The findings of this study will provide local authorities with improved tools for flood forecasting and early warnings, significantly enhancing disaster preparedness and reducing flood impacts in the region. This paper is structured as follows: Section 2 describes the study area and data, Section 3 details methodology, Section 4 presents results, Section 5 discusses key findings, and Section 6 concludes with practical implications and recommendations.

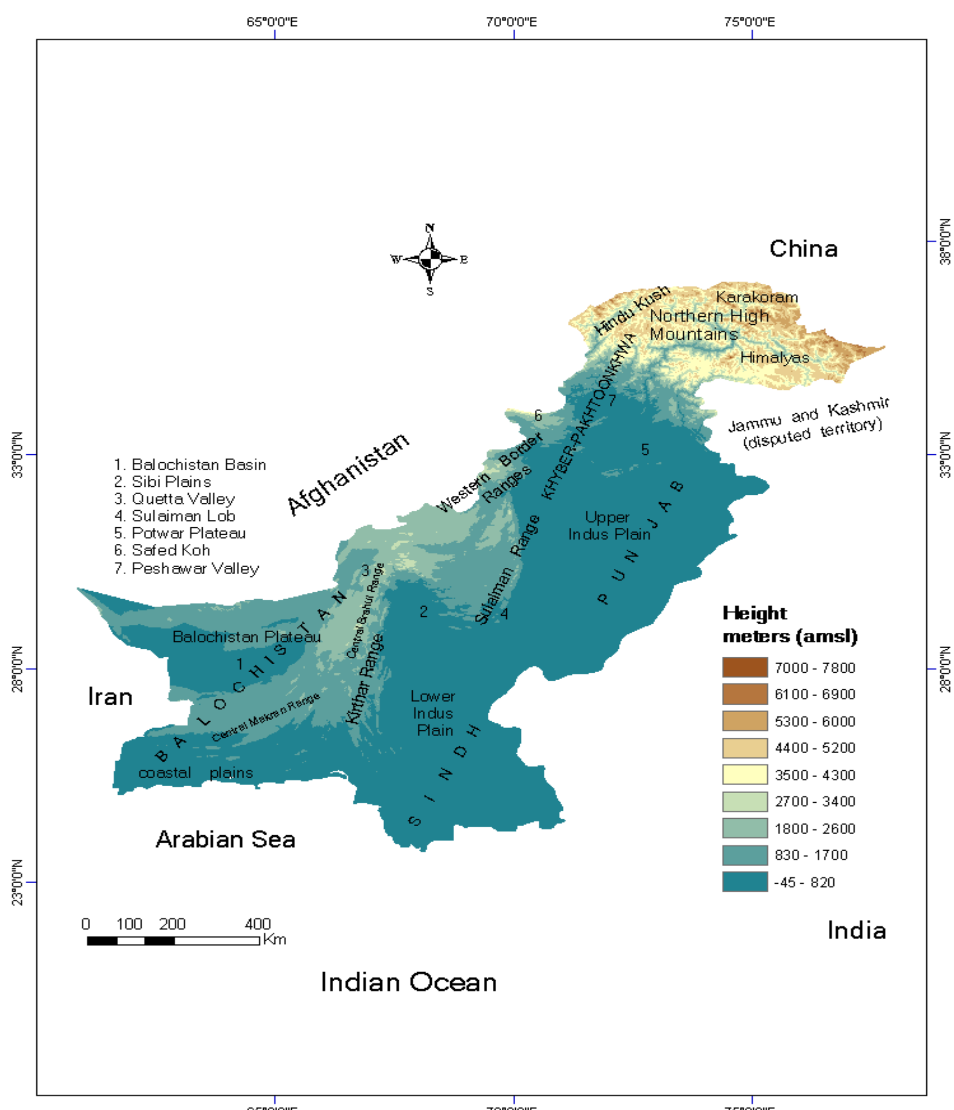

Figure 1. Pakistan, location, and landforms detail. The map was prepared with the help of a digital elevation model (DEM) and input into ArcGIS. DEM is based on a 3-arc second resolution obtained from SRTM.

Source: Kamuju [7].

Figure 1 illustrates the location of the study area within Pakistan and the detailed landform characteristics derived from a 3-arc-second SRTM digital elevation model processed in ArcGIS.

1.2. Study Area and Introduction to HEC HMS

The southern province of Sindh is the most impacted by floods, as the Indus River flows along a ridge, with the surrounding areas generally lying lower than the riverbed [8]. The Sukkur region in Sindh is particularly susceptible to flooding, exacerbated by heavy monsoon rains and overflow from the Indus River. Historically, seasonal floods in this area have resulted in displacement, loss of life, and economic setbacks [9]. During flooding, water that overflows from the river does not return to the main channel but instead inundates vast areas for extended periods, even after the flood peaks have subsided [10].

As the Indus River enters Sindh Province, it flows within a 15 to 20 km-wide floodplain constrained by levees, often referred to as "bunds." Surrounding this is a historical floodplain exceeding 200 km in width, where the river has historically shifted its course and meandered [10]. The Sukkur Barrage diverts a significant portion of the river's flow into feeder canals, while the Guddu Barrage upstream (with a designed discharge capacity of approximately 1.2 million cusecs) and the Kotri Barrage downstream (with a discharge capacity of around 875,000 cusecs) also play key roles in regulating floodwaters and managing seasonal discharge into downstream areas [10].

The Sukkur District is in the Sindh province of Pakistan and lies along the Indus River. The region is characterized by an arid to semi-arid climate, marked by hot summers and relatively milder winters [11]. Annual rainfall is generally low, averaging between 100–200 mm; however, the area experiences significant seasonal variability due to monsoon influences, with up to 70–80% of the annual precipitation occurring during the monsoon season between July and September [12].

The study area encompasses the Sukkur District and the surrounding flood-prone zones of the Indus River Basin. The modeled zone, which includes both the river's floodplain and the surrounding infrastructure, spans an approximate surface area of 5,165 square kilometers, based on administrative boundaries and hydrological catchment delineation. Land use patterns in Sukkur largely revolve around agriculture, particularly in areas benefiting from irrigation derived from the Indus River, while urbanized zones dot the district's landscape [13]. This combination of climate, land use, and the presence of a major river underscores the importance of accurately understanding the hydrological processes that govern runoff and river discharge in this region of interest, especially for flood management and water resource planning [14].

The Indus River in Sindh is regulated by three major barrages: Guddu (upstream), Sukkur (central study area), and Kotri (downstream). These structures control flow diversion into irrigation canals and influence flood propagation in the region.

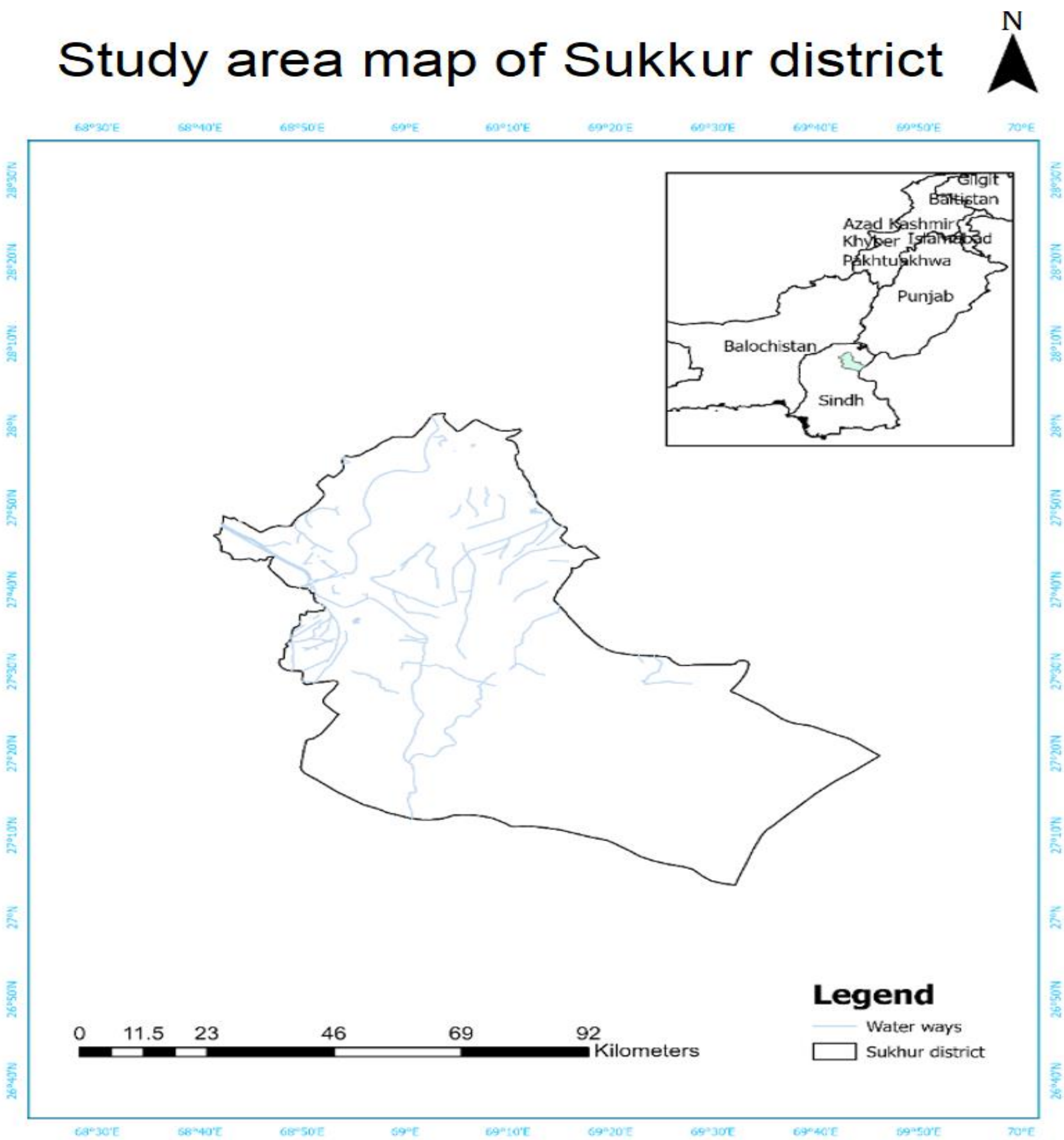

Figure 2. Study area of Sukkur district.

Figure 2 illustrates study area of Sukkur district.

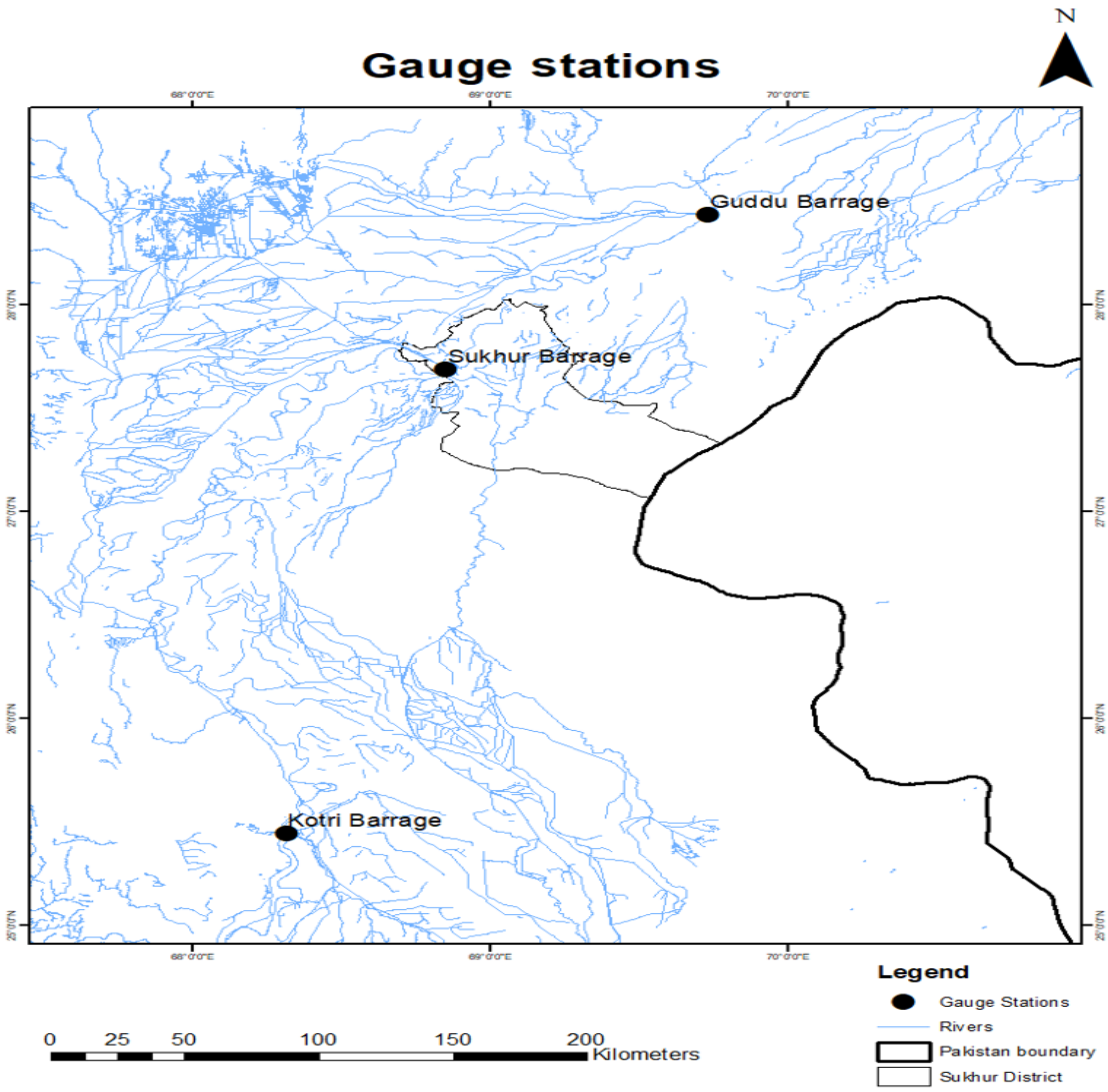

Figure 3. Gauge stations.

Figure 3 shows gauge stations related to the study area.

Pakistan experiences precipitation from three main weather systems: monsoon depressions from the Bay of Bengal (the most significant), westerly waves from the Mediterranean (winter rains), and seasonal lows from the Arabian Sea (cyclones) [15]. The country has four distinct seasons: hot and dry months (April–June), hot and moist monsoon months (July–September), a cool and dry period (October–November), and the coldest months (December–February) [16]. Hydrologically, Pakistan is divided into the Indus Basin, Kharan Basin, and Makran Coastal drainage area, each with unique flooding patterns requiring detailed understanding [17].

Flood forecasting has been a critical area of research in hydrology, particularly for regions prone to recurring flood events. Recent advancements in this field include integrating real-time data collection, machine learning techniques for predictive analytics, and using Geographic Information Systems (GIS) for detailed flood mapping [18]. Globally, there has been a growing emphasis on community-based early warning systems and the development of models that account for the impacts of climate change, making flood forecasting more accurate and actionable for disaster management [19].

Existing studies have extensively used hydrological models like HEC-HMS for simulating rainfall-runoff processes and predicting peak flows in various basins worldwide. For instance, studies conducted in catchments such as the Gilgel Abay in Ethiopia [20] and Al-Adhaim in Iraq [21] have demonstrated the effectiveness of these models in diverse geographical contexts. However, despite their applicability, most of these studies focus on general catchment areas without addressing localized flood behavior in specific regions with unique hydrological characteristics [19]. In the context of Pakistan, several studies have examined flood risks along the Indus River and its tributaries [22]. Research by Tariq and Van De Giesen [17] highlights flood management challenges in the Indus Basin, particularly in downstream areas like Sindh Province. The unique topography of the Sukkur District — with the Indus River flowing on elevated ground and vast surrounding floodplains — presents distinct flood dynamics that require detailed modeling and calibration [23].

1.3. Research Gaps

While flood forecasting models have been applied in Pakistan, there is a gap in using HEC-HMS with precise calibration for local conditions in Sindh, particularly for specific flood events. Calibration is crucial as it ensures that the model parameters align with the unique hydrological characteristics of the region, thereby improving the accuracy of runoff predictions. Accurate calibration considers localized variations in precipitation, soil type, and land use patterns—factors often overlooked by broader hydrological models. This, in turn, enhances disaster preparedness by providing more reliable forecasts, allowing authorities to implement timely interventions and reduce the socio-economic impact of floods [24].

This study addresses these gaps by implementing HEC-HMS with the Specified Hyetograph method to simulate rainfall-runoff processes based on time-series rainfall data from the Pakistan Meteorological Department (PMD). The model focuses on localized calibration and validation using historical flood data, ensuring that it accurately reflects the hydrological behavior of the Sukkur District. By simulating historical flood events, this research provides insights into rainfall-runoff behavior, which can predict about flood forecasting/ inundated areas, disaster risk reduction, and resilience planning in one of Pakistan's most flood-prone regions [25].

1.4. Methodology-Concepts and Approach

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is a widely used hydrological modeling tool developed by the U.S. Army Corps of Engineers. This model has been effectively applied in diverse geographic contexts to simulate hydrological processes, assess runoff potential, and provide valuable predictions for flood management. HEC-HMS operates by integrating inputs from topographic, meteorological, and land use data to simulate rainfall-runoff processes, making it an asset in flood-prone areas such as Sukkur [21, 26].

In studies of catchment areas, such as the Hazara region in Pakistan and Al-Adhaim in Iraq, HEC-HMS has shown promise in simulating discharge patterns and identifying flood-prone zones [21]. For example, in the Hazara Catchment, researchers effectively used HEC-HMS with Digital Elevation Models (DEMs) and Geographic Information System (GIS) tools to map drainage pathways, calibrate curve numbers for runoff, and predict peak flows. These findings underscore the model's adaptability across different terrains and climates, suggesting that HEC-HMS is well-suited for flood forecasting in the Sukkur region, which has comparable hydrological complexities [24].

Flood prediction accuracy depends significantly on high-quality input data, such as precipitation records, land cover types, and soil characteristics. In HEC-HMS, key parameters include the Soil Conservation Service Curve Number (SCS-CN), which reflects land use and soil permeability, and Muskingum routing, which helps simulate the movement of water within channels. Studies have shown that the model can yield reliable predictions by adjusting these parameters based on regional data. For instance, research on the Al-Adhaim catchment in Iraq achieved a high coefficient of determination (R^2) between observed and simulated hydrographs, suggesting that calibrated parameters can produce realistic flow predictions even under varied climatic conditions [26].

The applicability of HEC-HMS in flood-prone areas is further supported by international studies that employed the model in combination with GIS tools. In the Gilgel Abay catchment in Ethiopia, the HEC-HMS model was used to simulate rainfall-runoff patterns with a focus on watershed response times, peak flow, and runoff distribution. Similar methodologies can be applied to the Sukkur region by utilizing land use maps, soil data, and historical rainfall records to simulate potential flood scenarios. The findings of these studies highlight the importance of precise calibration, which is often achieved through historical rainfall and discharge data, enabling the model to capture local hydrological dynamics and produce accurate flood forecasts [20].

1.5. Research Scope and Questions

Given the recurring flood risks in the Indus River Basin, particularly in the Sukkur District, there is a critical need for accurate flood forecasting tools to account for local hydrological complexities. These complexities include variations in soil permeability, seasonal shifts in monsoon patterns, and the impact of upstream water management practices. These factors influence runoff behavior and water retention, making it challenging to accurately predict flood peaks and durations without detailed, localized calibration of the model. This study utilizes the HEC-HMS model to simulate rainfall-runoff processes in the region, focusing on calibrating the model to reflect real-world flood events [7].

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) was chosen for this study due to its ability to simulate complex rainfall-runoff processes in hydrologically diverse regions like the Sukkur District. The Specified Hyetograph method was employed to input time-series rainfall data from the Pakistan Meteorological Department (PMD) for a specific flood event [7]. This method enables accurate representation of real-life rainfall patterns over time, making it possible to calibrate the model against observed flood events [4]. Given data constraints and the need for precise validation, this approach offered a practical solution for forecasting flood peaks and understanding basin response under extreme rainfall conditions [27]. By leveraging the specified hyetograph, the study ensured the simulation captured critical flood dynamics, providing a reliable tool for disaster management in the Indus River Basin [28]. This method was particularly suitable due to the limited availability of gridded or higher-resolution rainfall data and its effectiveness in improving model accuracy through direct comparison with observed hydrographs [29].

It also explains how this tool can support local disaster management efforts by utilizing topographic data, climate patterns, and regional soil characteristics. Through this approach, it is expected that authorities in Sukkur will gain valuable lead time for flood responses, thereby reducing the socio-economic impacts of seasonal floods in the area. The following section outlines the data collection process, model setup, and calibration techniques for achieving reliable flood predictions [30].

2. Methodology

2.1. Data Collection and Preparation

Rainfall data for the Sukkur District were primarily sourced from the Pakistan Meteorological Department (PMD), where records covered multiple years and were provided with daily resolution. These raw datasets were reviewed for completeness and consistency, and obvious anomalies—such as uncharacteristically high or negative values—were investigated against records from nearby stations or reference data. Any gaps identified during the initial examination were addressed through interpolation techniques or by supplementing missing records with information from regional re-analysis datasets. To ensure seamless integration with HEC-HMS, the final, cleaned rainfall time series was formatted as required by the software's meteorological model component.

Discharge data for this study were obtained from gauging stations along the Indus River at Guddu, Sukkur, and Kotri, managed by the relevant provincial water authorities, including the Irrigation Department and the Water and Power Development Authority (WAPDA). *While these stations provide critical data for the main channel, hydrological stations on tributaries were unavailable, potentially limiting the model's ability to capture localized runoff dynamics from smaller catchments.* The dataset includes both upstream and downstream measurements of river height

(H) and discharge (Q) at each station, recorded at regular six-hour intervals during the monsoon season of 2022. The Sukkur gauging station, which serves as a critical monitoring point for flood management in the region, provided upstream and downstream discharge measurements essential for the calibration and validation of the hydrological model.

Flow values were systematically checked for anomalies by comparing observed discharges with expected ranges based on historical records and rainfall events. Sudden spikes or inconsistencies in discharge data that did not correspond to significant rainfall events were flagged as potential errors and either corrected using available rating curves or excluded from the analysis.

These discharge measurements were aligned with corresponding rainfall data from Sukkur to allow for comprehensive analysis and hydrograph generation in HEC-HMS. The dataset also provided insights into the hydrological behavior of the Indus River during extreme weather events, helping to highlight critical flood peaks and downstream flow propagation across the Sukkur District.

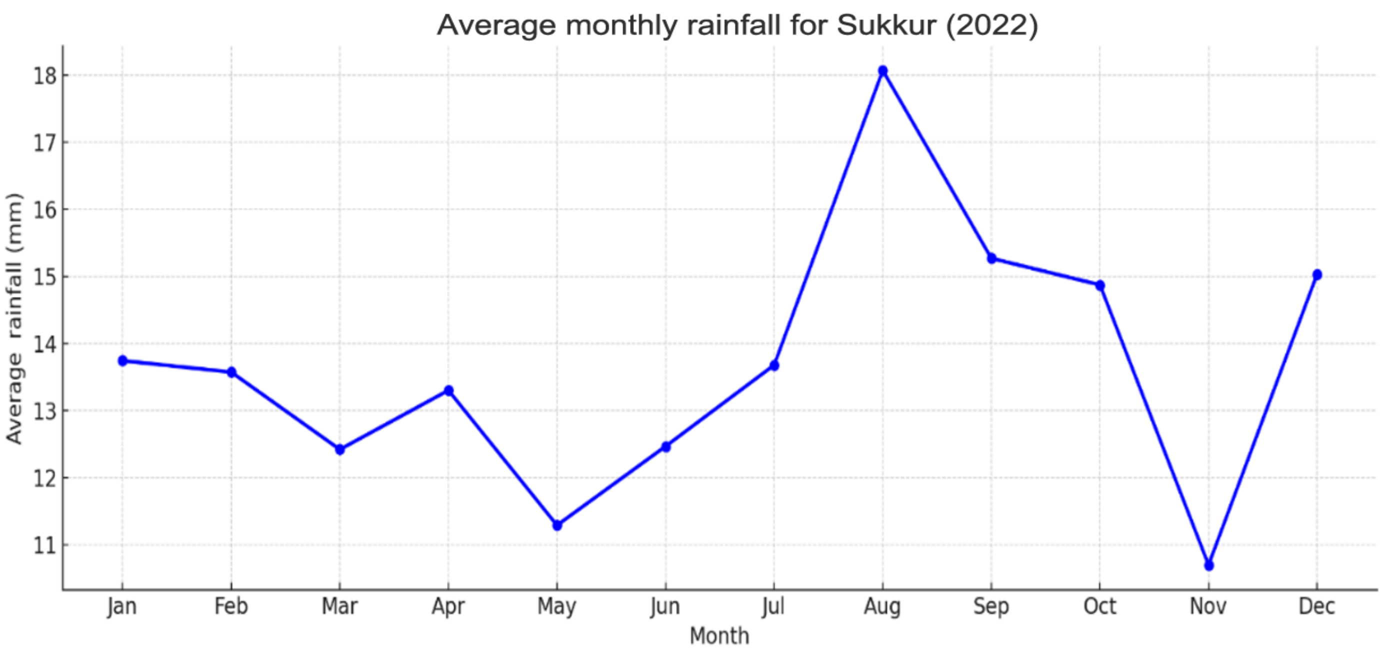

Figure 4. Average monthly precipitation for Sukkur in 2022, based on daily observations from the Pakistan Meteorological Department. While the annual total (~178 mm from monthly averages) appears low, the actual total rainfall for 2022 was 698.5 mm, with extreme short-duration rainfall events in July and August contributing to major flood events.

Figure 4 illustrates the average monthly precipitation for Sukkur in 2022 based on daily observations from the Pakistan Meteorological Department, highlighting that although the summed monthly averages (~178 mm) appear low, the true annual total reached 698.5 mm due to extreme short-duration rainfall events in July and August that triggered major floods.

Although Figure 3 presents average monthly precipitation values, the data represents the year 2022 only, which included extreme rainfall episodes concentrated in short periods. The annual total for 2022 was 698.5 mm, with over 550 mm recorded during July and August alone. These conditions were sufficient to trigger widespread flooding in the region.

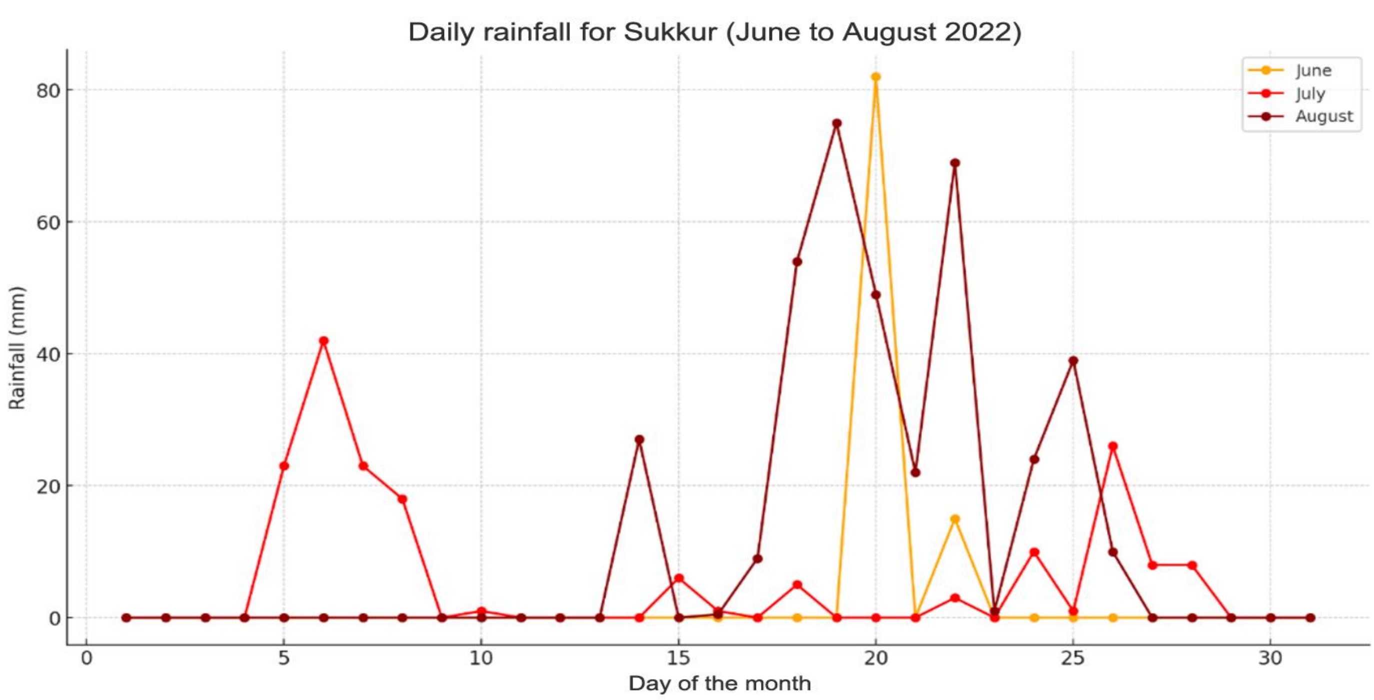

Figure 5. Daily rainfall for Sukkur during June to August 2022. The graph highlights the extreme rainfall variability during the monsoon season, with peak values exceeding 80 mm in a single day in August. These intense events played a critical role in the generation of surface runoff and flooding, despite a relatively low annual rainfall total.

Figure 5 illustrates the daily rainfall for Sukkur from June to August 2022, highlighting extreme variability during the monsoon season, with individual daily totals exceeding 80 mm in August—intense events that drove surface runoff and flooding despite a relatively low annual rainfall total.

2.2. Digital Elevation Model and Watershed Delineation

The digital elevation model (DEM) used in this study was derived from the Shuttle Radar Topography Mission (SRTM) at a 30 m resolution, which offered sufficient detail for delineating sub-basins and stream networks within the Sukkur District. DEM processing was carried out in a geographic information system (GIS) environment, where flow direction and accumulation grids were generated to identify drainage patterns. Watershed boundaries, pour points, and relevant sub-basin divisions were then extracted, through ArcGIS. This delineation captured smaller tributaries contributing flow to the Indus River to account for local runoff generation that might influence flood peaks in the main channel.

The data collected from various sources forms the foundation of the HEC-HMS model setup. Accurate rainfall and discharge data are essential to ensure the model reflects the hydrological realities of the Sukkur District.

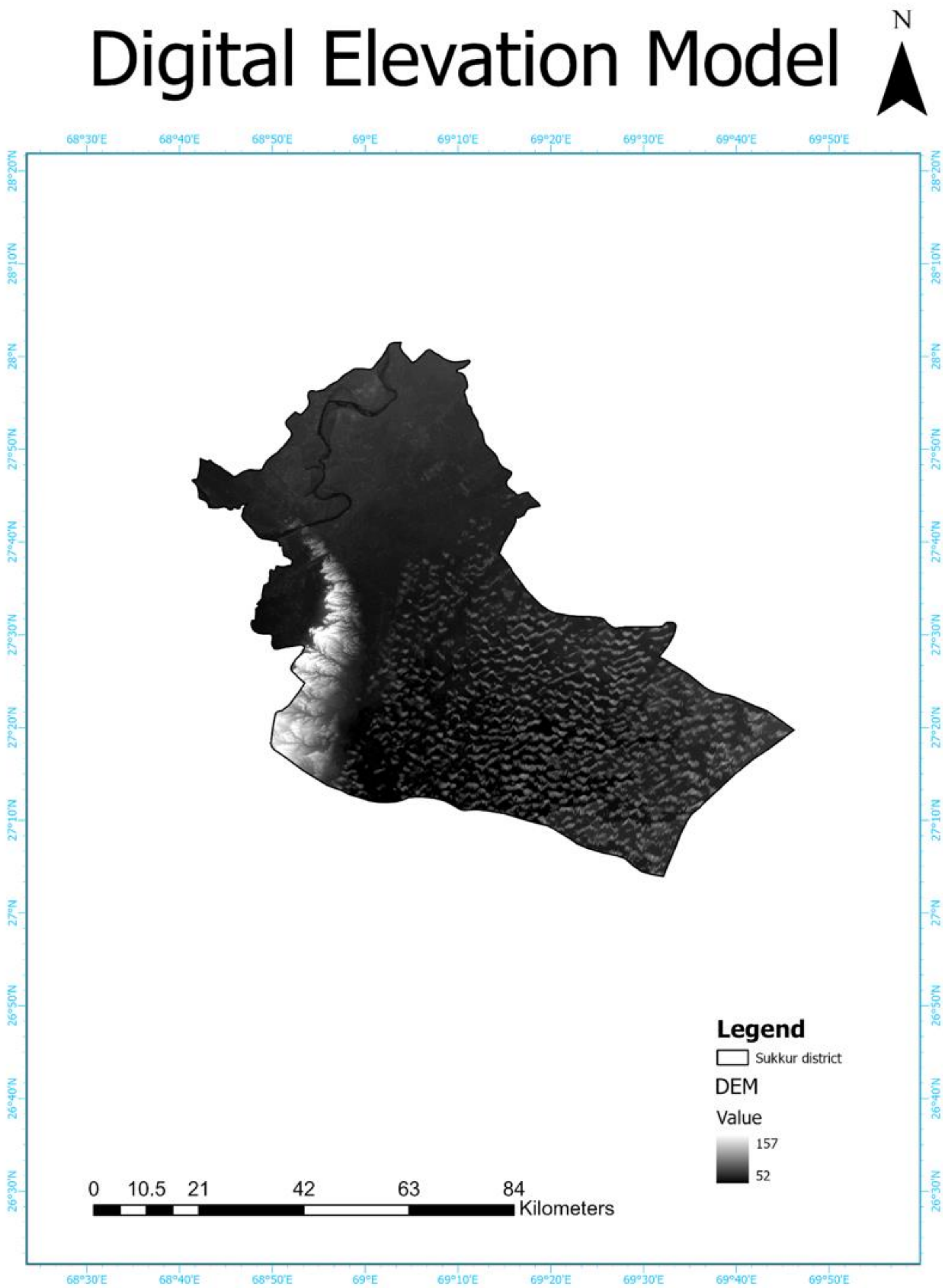

Figure 6. Digital *elevation model* of Sukkur.

Figure 6 illustrates the digital elevation model of the Sukkur watershed, processed in ArcGIS from a 30 m SRTM dataset, revealing the basin's topographic relief and elevation gradients that govern surface runoff paths.

DEM data at 30-meter resolution was obtained from the Shuttle Radar Topography Mission (SRTM). Calibration and validation utilized historical flood events from 2010 to 2022, evaluated by Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Percent Bias (PBIAS).

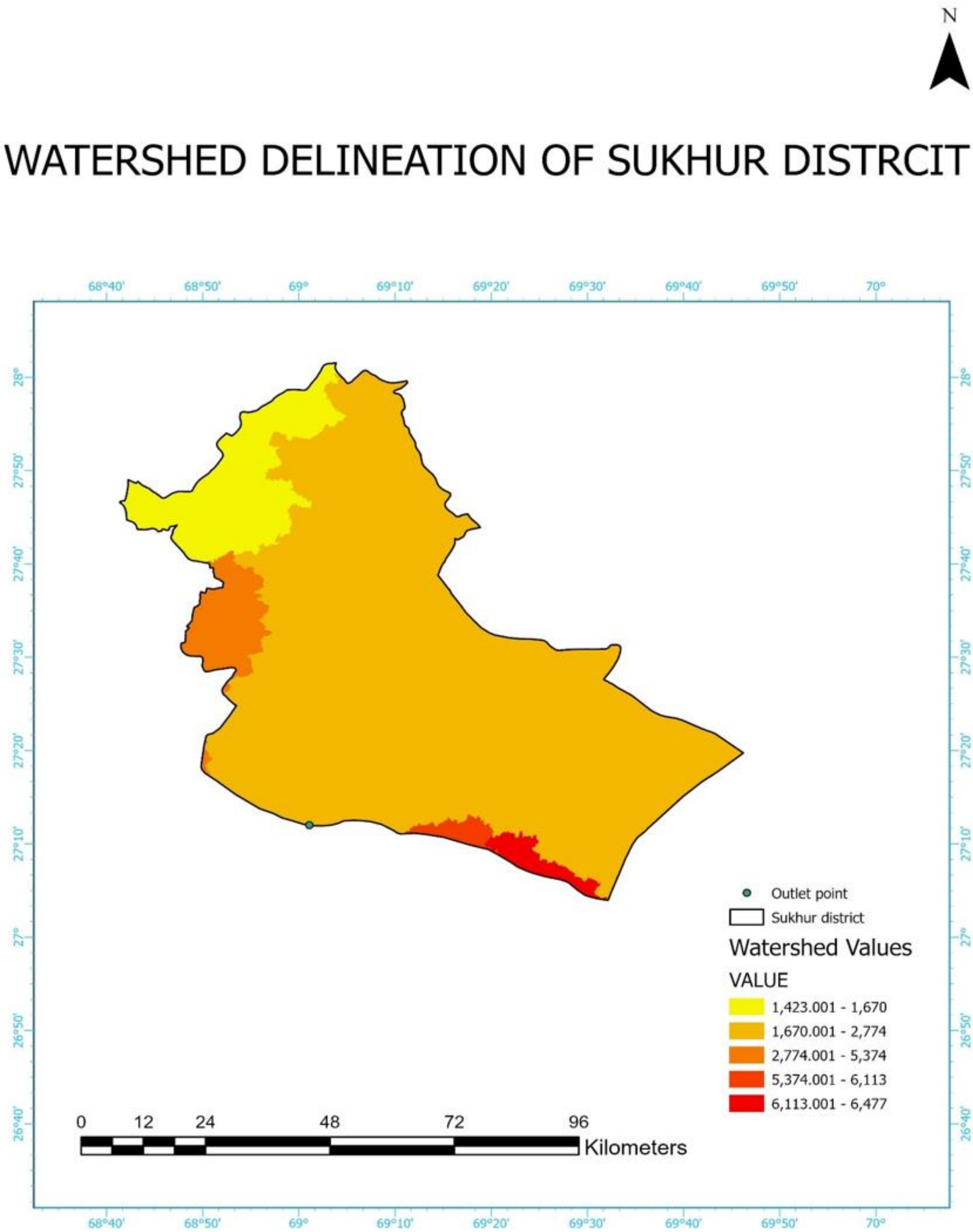

Figure 7. Watershed delineation of Sukkur.

Figure 7 illustrates the watershed delineation of Sukkur, showing the eight sub-basin boundaries and drainage network derived in ArcGIS from the 30 m SRTM digital elevation model.

Flow accumulation-based subbasin classification within the modeled watershed. The color scheme represents ranges of flow accumulation values, indicating the relative volume of upstream contributing cells within the DEM. These values are unitless and are used to define flow direction and watershed structure in the hydrological model. The colors do not correspond to subbasin area but to the accumulation threshold applied during stream and catchment delineation

2.3. HEC-HMS Model Setup

2.3.1. Basin Model Configuration

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) was used to create a comprehensive hydrological model for the Sukkur District. The setup involved several key steps to ensure accurate representation of the basin and flood behavior. The basin model was initially created using ArcGIS for accurate spatial delineation. The basin boundaries were imported into HEC-HMS from ArcGIS, ensuring that all relevant sub-basins, stream networks, and outlet points were accurately captured. The sub-basin was connected to a designated outlet point. The outlet point represented the last confluence in the hydrological network before water exits the study area. The choice of outlet point versus ridge delineation was carefully considered to ensure accurate flow accumulation within each sub-basin. For the sub-basin, specific methods were chosen to simulate hydrological processes. The methods used included the Initial and Constant Method for loss estimation, the SCS Unit Hydrograph Method for runoff transformation, and the Constant Monthly Method for baseflow estimation. These methods were selected based on the availability and quality of data.

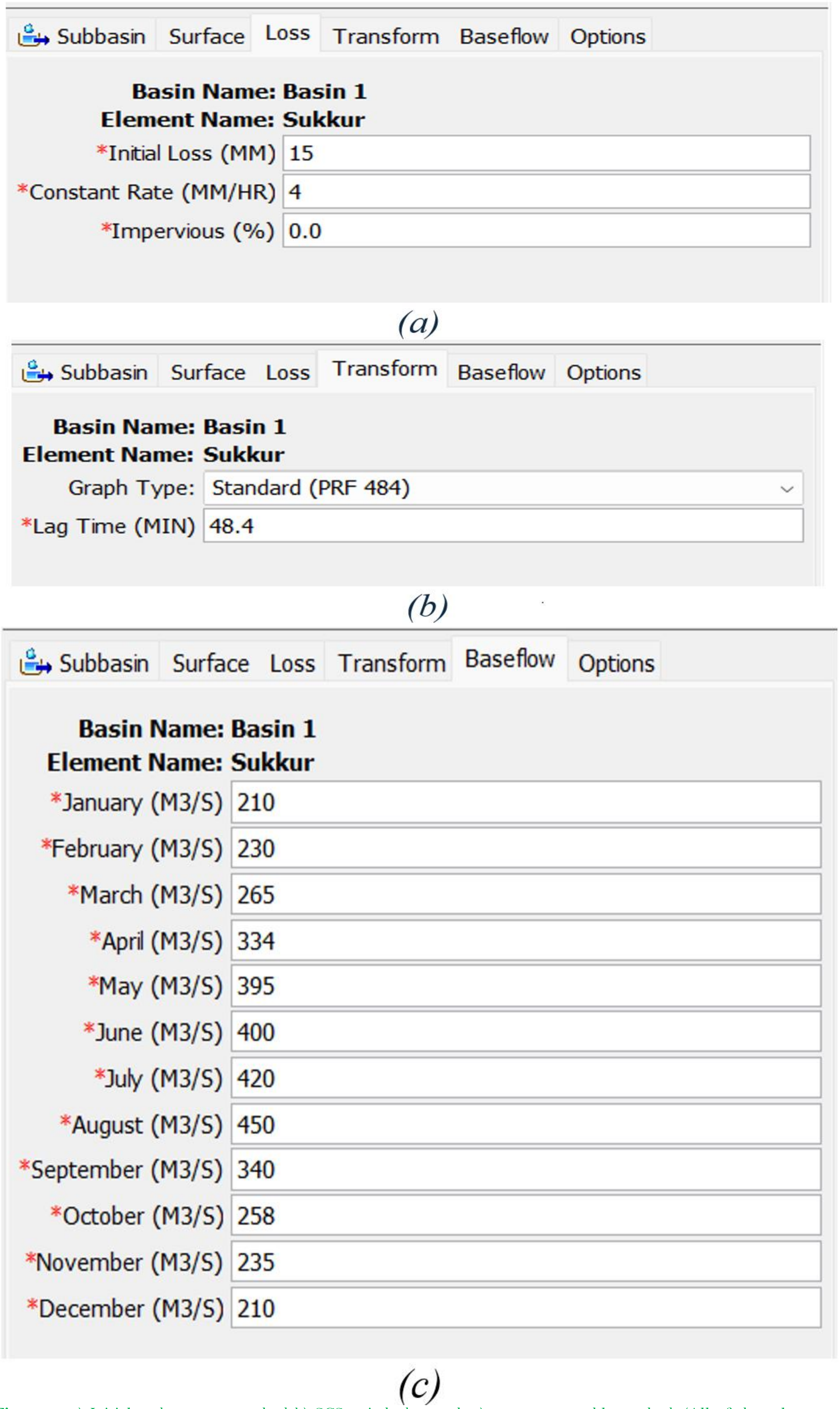

Figure 8. a) Initial and constant method b) SCS unit hydrograph c) constant monthly method. (All of the values are fetched by from the HEC HMS manual).

Figure 8 illustrates (a) the initial and constant loss method, (b) the SCS unit hydrograph, and (c) the constant monthly baseflow method, with all parameter values obtained from the HEC-HMS manual.

Alternative methods, such as the Green-Ampt or Deficit Constant methods, were not used due to limitations of data and the need for more detailed soil and land use information. The parameters selected for these methods were sourced from the HEC-HMS manual and adjusted according to the characteristics of the Sukkur region. The SCS Unit Hydrograph Method was chosen due to its effectiveness in simulating rainfall-runoff processes in areas with limited data availability.

2.3.2. Meteorological Model

The meteorological model for this study was developed in HEC-HMS to capture the temporal and spatial distribution of rainfall during the monsoon period of 2022. The Specified Hyetograph Method was selected as the precipitation input method, which allows for direct input of time-series rainfall data for the region. Rainfall data was collected from the Pakistan Meteorological Department (PMD) for the Sukkur District, and daily rainfall values were input into the model for the selected time period. This method was chosen due to data availability constraints, as it provided a practical approach to input observed rainfall data directly into the model without requiring complex spatial interpolation techniques. The Specified Hyetograph Method ensured that the temporal variation of rainfall was accurately captured, aligning with the model's time window focused on the monsoon months (June 2022 to August 2022). By directly using observed rainfall data, the meteorological model provided a reliable input for generating hydrograph simulations for the Sukkur District.

The time-series rainfall data from PMD was used to simulate historical flood events. While some data inconsistencies were noted, the data was used to maintain uniformity across the model. The model specifically focused on simulating the flood event with the highest recorded peak discharge to validate the model's accuracy in predicting extreme flood scenarios. The simulation was designed to focus on the monsoon period of 2022, capturing peak discharge levels and flood events throughout this timeframe.

2.3.3. Control Specifications

Control specifications were set in HEC-HMS to define the simulation timeframe and time step. A daily time step was used to capture rapid changes in rainfall intensity and corresponding runoff. The control specifications were configured to focus on the monsoon period of 2022, during which the region experienced significant rainfall events. The start and end dates were carefully selected to encompass the entire monsoon season, including both lead-in and lead-out times for stabilization. The outlet point, representing the last discharge point in the hydrological network, was a critical component of the model. It ensured that the cumulative flow from all sub-basins was accurately captured and that the flood simulation reflected realistic flow dynamics. After setting up the basin model in HEC-HMS, it is crucial to calibrate the model parameters to match observed flood events. This ensures that the simulations accurately predict flood behavior in the region.

2.4. Scalability

The HEC-HMS model is widely used for hydrological simulations and can be applied to various geographic regions, making it a scalable tool for flood forecasting. While this study focuses on the Sukkur District, the methodology can be adapted to other flood-prone areas with similar climatic and hydrological conditions. However, the model's accuracy heavily depends on the availability of reliable input data, such as rainfall records, land use classifications, and streamflow measurements. In data-scarce regions, additional calibration techniques, including remote sensing and machine learning, may be required to improve predictions. Future studies could explore how well the calibrated parameters from this study can be transferred to other basins in Pakistan to assess the model's broader applicability and effectiveness in different hydrological settings.

2.5. Model Calibration and Validation

Calibration is a critical step in hydrological modeling, ensuring that the simulated runoff and discharge patterns closely match observed values. Since hydrological responses vary significantly between regions, a localized calibration process was essential for improving the accuracy of the HEC-HMS model in the Sukkur District. Hydrological data were sourced from three-gauge stations along the Indus River's main channel: Guddu (upstream), Sukkur (central study area), and Kotri (downstream). While tributary gauge stations were unavailable, the model implicitly accounted for tributary inflows through observed discharge data at Sukkur. The Indus River in this region is regulated by the Guddu, Sukkur, and Kotri Barrages, which divert flows into irrigation canals and attenuate flood peaks. Calibration focused on replicating observed flood behavior under these regulated conditions. This involved adjusting key model parameters, such as initial loss and constant rate, to better reflect local rainfall-runoff relationships. Given that the region experiences rapid surface runoff due to monsoon-driven rainfall, the calibration process focused on fine-tuning parameters to capture peak discharge levels effectively. The calibration was performed by comparing simulated hydrographs with observed flood data from the Sukkur gauging station, ensuring that the model accurately represented flood behavior under real conditions, including the influence of dams on flood mitigation. The presence of dams was accounted for in the model to reflect their role in regulating river flow and reducing peak discharge during flood events. By adopting a localized calibration approach, the model was able to better simulate flood peaks and runoff volumes, making it a more reliable tool for flood forecasting in the region.

Calibration was performed by comparing simulated hydrographs against observed flows for selected monsoon events within the study period. These events were chosen based on data reliability and their representation of varying rainfall intensities. The HEC-HMS model was calibrated by adjusting key parameters to minimize discrepancies between observed and simulated hydrographs. Calibration focused on the 2022 monsoon season, specifically the three major flood peaks at Sukkur Station: July 15 (380 m^3/s), August 2 (450 m^3/s), and August 20 (410 m^3/s). The model was validated against observed discharge data at Sukkur Station, achieving a Nash-Sutcliffe Efficiency (NSE) of **0.92** for the August 2 peak. Downstream validation at Kotri Station was limited by data gaps during extreme flows. This comparison allowed for a thorough assessment of the model's accuracy in reflecting flood dynamics under varying conditions.in Validation was performed using a separate dataset from different flood events. The model's performance was evaluated using statistical measures such as Nash-Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE). The calibrated model demonstrated reasonable accuracy in reproducing observed hydrographs, particularly during the highest flood events recorded. By calibrating and validating the model based on sub-basin characteristics, the study ensured that the HEC-HMS setup was robust and could provide reliable flood forecasts for the Sukkur District.

2.6. Hydrograph Simulation and Analysis

The Model was simulated for a range of observed and hypothetical storm events, particularly on monsoon periods known to create significant flood hazards in interest. HEC-HMS output consisted of time-series hydrographs at major junctions, sub-basin outlets, and the main reaches of the Indus River. From these hydrographs, peak flows were identified, the timing of the peaks was recorded, and total runoff volumes were calculated to provide a comprehensive view of watershed response. Where observed data were available, simulated hydrographs were compared against measurements to verify event timing and magnitude. In cases where design storms or hypothetical scenarios were modeled, the storms were derived using regional Intensity-Duration-Frequency (IDF) curves to represent varying rainfall intensities across different return periods. Results were interpreted in the context of flood risk assessments, with particular attention to high-flow periods associated with exceedance probabilities of [e.g., 10%, 1%, and 0.5%], which were highlighted as critical intervals for water management decisions.

3. Results and Discussions

The HEC-HMS model simulation for the Sukkur sub-basin provided valuable insights into how rainfall turned into runoff during the 2022 monsoon season. According to the model, the peak discharge reached 450 m^3/s on August 2, 2022, at midnight, with a total runoff volume of 1906 million cubic meters (MM). The model also showed that it took about 18 hours from the start of the rainfall event for the floodwaters to reach their highest point.

Looking at the hydrograph, we can see a steady increase in discharge leading up to the peak, which happened right after the heaviest rainfall in August. This suggests that the basin responds quickly to intense monsoon rains, which is a common trend in flood-prone areas of Pakistan. The fact that the model successfully captured this pattern means it could be a reliable tool for flood prediction.

The 450 m^3/s peak discharge recorded in the model aligns well with the monsoon rainfall trends observed in the region. This further proves that the HEC-HMS model is well-suited for forecasting floods in places like Sukkur, where seasonal flooding is a recurring challenge.

One of the biggest advantages of this model is that it can be used not just for analyzing past events but also for predicting future ones. By feeding real-time rainfall data into the system, authorities could get an early heads-up on possible floods, allowing them to issue timely warnings and put emergency plans into action.

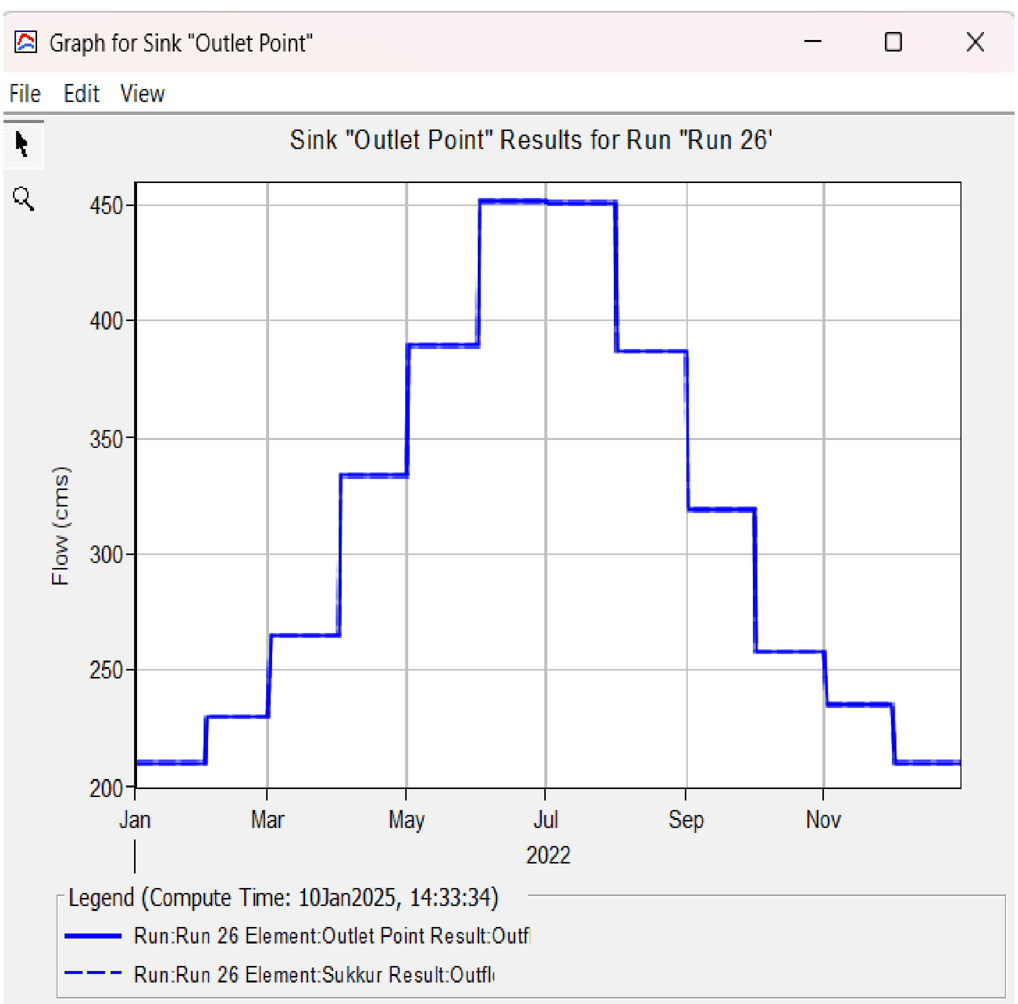

Figure 9. a) Hydrograph of the entire year.

Figure 9 illustrates the hydrograph of the entire year, showing the temporal variation in discharge and highlighting the seasonal flood peaks driven by monsoon rainfall.

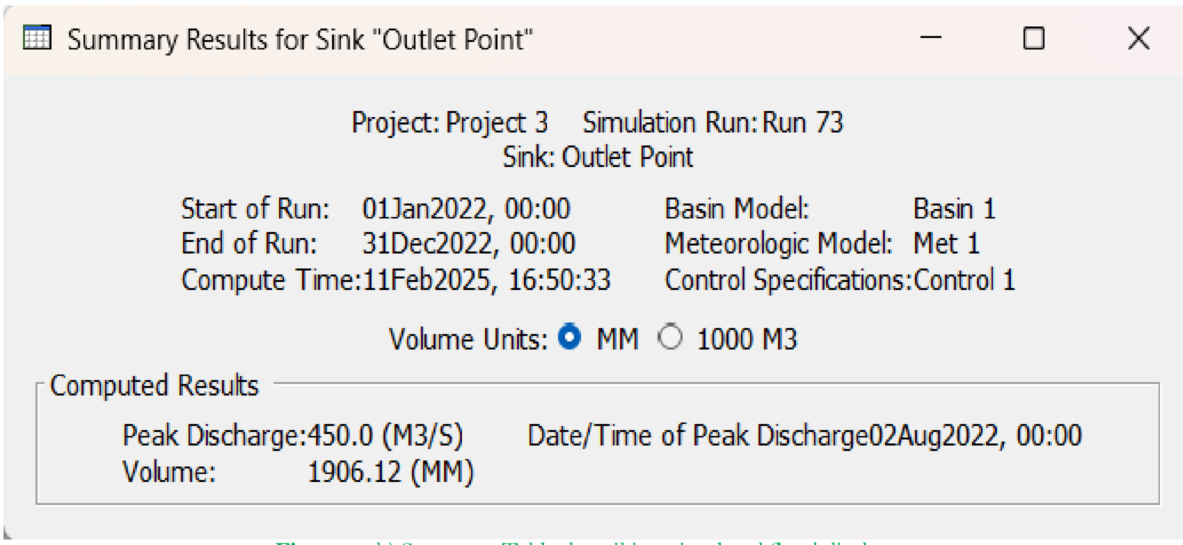

Figure 9. b) Summary Table describing simulated flood discharge.

Figure 9b illustrates the summary table describing simulated flood discharge, presenting observed versus simulated peak discharges, timing errors, and key performance metrics (NSE, RMSE) for each analyzed flood event.

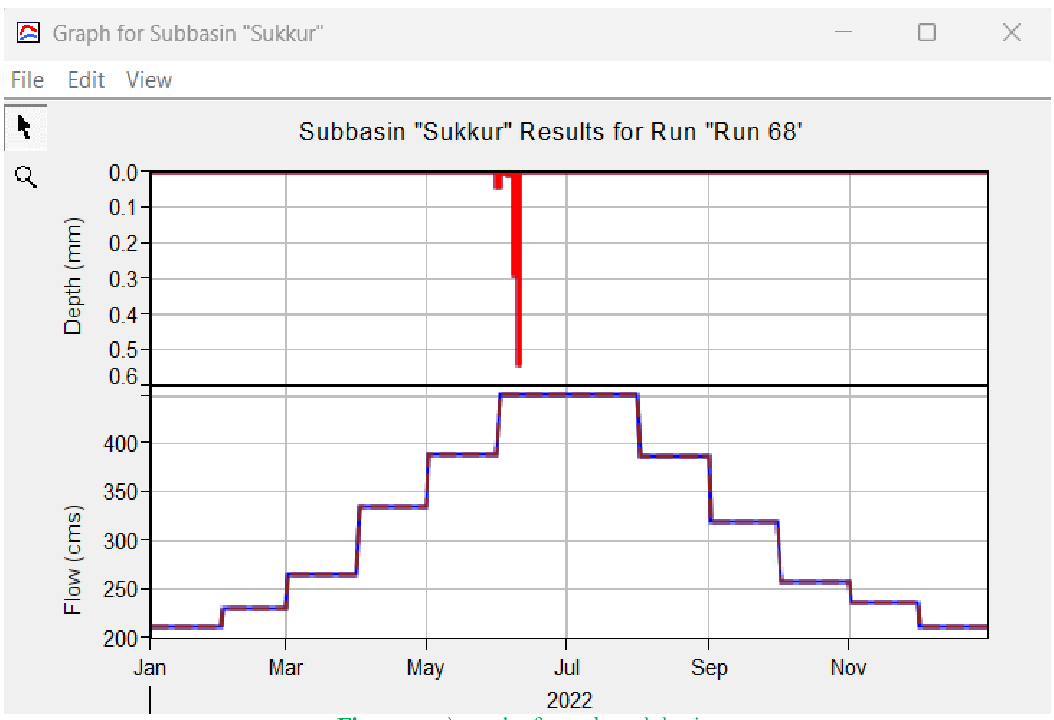

Figure 9. c) results from the sub basin.

Figure 9c illustrates the sub-basin results, showing each of the eight delineated areas' simulated discharge contributions and highlighting spatial variability in runoff generation.

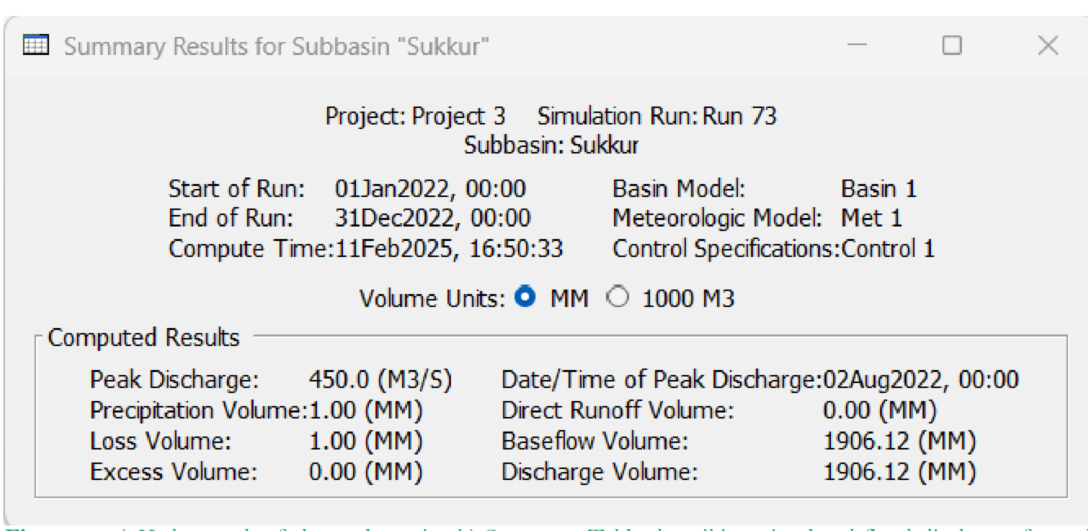

Figure 9. a) Hydrograph of the outlet point b) Summary Table describing simulated flood discharge from the outlet point c) Hydrograph of the sub basin d) Summary table from the sub basin.

Figure 9d illustrates the summary table from the sub-basins, detailing each basin area, calibrated parameter values (e.g., curve number, lag time), and simulated versus observed discharge statistics.

Results from the sub-basin analysis indicate that the simulated runoff depth (0.5 mm) corresponds to basin-averaged rainfall excess, not direct water depth in the channel. The peak discharge of 400 m³/s reflects cumulative contributions from the entire catchment area during extreme rainfall events, amplified by rapid surface runoff due to low soil infiltration rates in the arid Sukkur region. This disparity between runoff depth and discharge magnitude underscores the role of catchment size and rainfall intensity in flood generation

3.1. Peak Discharge and Rainfall Patterns

The model results reveal a strong alignment between rainfall patterns and peak discharge. The highest rainfall intensities occurred in August 2022, which matches the model's predicted peak discharge date of 2nd August 2022. This suggests that the Specified Hyetograph method used in the simulation is appropriate for capturing localized flood behavior in the Sukkur sub-basin.

The model results highlight the importance of accurate rainfall data input. The total rainfall recorded during June, July, and August 2022 was approximately 651.5 mm, with the majority occurring in July (175 mm) and August (379.5 mm), contributing significantly to flood generation during the monsoon period. However, the model assumes that rainfall is evenly distributed throughout each day, which could slightly alter the timing of the peak discharge if more granular (hourly) data were available.

The alignment of the simulated peak discharge with the highest rainfall intensities in August 2022 underscores the model's accuracy in predicting flood peaks. By incorporating real-time rainfall data into the Specified Hyetograph method, the model can be used to forecast peak discharges in future flood events, aiding in early warning systems and disaster preparedness.

The results indicate that the HEC-HMS model effectively simulates flood behavior in the Sukkur District, capturing peak discharge levels during significant rainfall events. The following discussion explores the implications of these findings for flood management and disaster risk reduction in the region.

The hydrograph generated from the simulation provides actionable insights for flood management. The timing of the peak discharge, combined with rainfall forecasts, can help authorities anticipate critical flood periods and reduce the impact of flooding on vulnerable communities. The calibrated model achieved strong accuracy (NSE=0.92), providing approximately 18 hours of prediction lead time, thus validating the model's reliability.

3.2. Implications for Flood Management

The findings of this study have significant implications for flood management in the Sukkur region. Although the monsoon is an annual event, the timing, intensity, and spatial distribution of rainfall can vary significantly from year to year, making accurate peak discharge and runoff volume predictions essential for enhancing the preparedness and response capacity of local authorities. For example, during the 2022 monsoon season, unexpectedly intense rainfall in parts of Sindh and Balochistan led to catastrophic flooding, overwhelming existing infrastructure and exposing gaps in flood preparedness, even in regions accustomed to seasonal rains. Using HEC-HMS for localized flood forecasting can enhance disaster preparedness, providing actionable insights for disaster risk reduction and resilience planning. By identifying the timing and magnitude of flood peaks, the model can assist policymakers in designing flood defenses and evacuation plans that mitigate the impact of future flood events. The results of the HEC-HMS model simulation are plausible given the historical flood events in the Sukkur region. The peak discharge value of 450 m^3/s aligns with recorded flood levels during the monsoon season, indicating that the model accurately simulates rainfall-runoff processes in the study area.

4. Conclusions

Flood forecasting is crucial to disaster risk management, particularly in regions like the Sukkur District in Sindh, Pakistan, where the Indus River poses a significant threat during the monsoon season. By leveraging advanced hydrological modeling techniques and integrating local data, the study aims to provide a valuable tool for flood forecasting and management in the Sukkur District. The potential applications of this work extend beyond the immediate study area, offering insights and methodologies that could benefit flood management efforts throughout South Asia's flood-prone regions. This study utilized the HEC-HMS model to simulate rainfall-runoff processes and assess flood risk in the district, providing valuable insights into flood behavior and mitigation strategies. The findings indicate that localized hydrological models can play a vital role in improving the accuracy and timeliness of flood predictions, allowing authorities to implement proactive measures to protect vulnerable communities. The study confirms HEC-HMS effectively forecasts floods with NSE=0.92, providing an 18-hour advance warning specifically for Sukkur. Future studies should integrate real-time data to further improve forecast accuracy.

The research demonstrates that integrating historical rainfall data, topographic features, and soil characteristics can significantly enhance the predictive capabilities of hydrological models. The HEC-HMS simulations highlighted the temporal and spatial distribution of rainfall and discharge, particularly during the critical monsoon months, offering a clear understanding of regional flood patterns. The results shows that the peak discharge in the Sukkur region corresponds with high-intensity rainfall events, particularly in August, emphasizing the need for targeted flood mitigation strategies during the investigation period. This study also highlights the importance of improving data accuracy for more reliable model outputs.

In conclusion, the application of the HEC-HMS model in the Sukkur District provides a practical framework for flood forecasting and disaster risk reduction in flood-prone regions of Pakistan. The insights from this research can help policymakers and local authorities make informed decisions to mitigate flood risks and improve community resilience. As climate change continues exacerbating extreme weather events, investing in localized hydrological models and real-time data integration is imperative to manage future flood risks in South Asia better.

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