

RUNOFF SIMULATION IN THE UPPER INDUS BASIN USING HEC-HMS AND GIS-BASED MODELING TECHNIQUES

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Abstract

Water, a vital resource for life and agriculture, faces escalating global scarcity, especially in developing countries where irrigation consumes most freshwater, highlighting the urgent need for better planning and management despite limited hydrological data. The Hydrologic Modeling System (HEC-HMS) was applied to simulate runoff in the Gilgit River Basin, a key tributary of the Upper Indus Basin. The model integrates meteorological and spatial datasets from 1984 to 1998 to perform continuous runoff simulation. Using ArcGIS and the HEC-Geo HMS extension, the watershed was delineated, sub-basins identified, and key hydrological parameters were derived. Model calibration was conducted using observed streamflow data for the year 1984 and extended to a 10-year period, followed by validation for the years 1995 to 1998. The model showed satisfactory performance with RMSE, SSR, and PWRMSE errors of 8.5%, 9.6%, and 3.4% respectively. The results indicate the suitability of HEC-HMS for hydrological simulation and runoff forecasting in the Upper Indus Basin and highlight its potential for sustainable water resource planning in the region.

Keywords: HEC-HMS, GIS, Runoff Simulation, Upper Indus Basin, Hydrological Modeling, Gilgit River.

1. INTRODUCTION

Water is an essential natural resource, vital for sustaining life and supporting agricultural, domestic, and industrial activities. However, global water scarcity is escalating, particularly in developing countries where agriculture consuming approximately 80–89% of freshwater remains the primary sector dependent on irrigation Shakir et al., (2010); IWMI, (2000). The growing gap between water availability and demand necessitates improved planning, development, and management strategies, which are often hindered by limited hydrological data (Khanam et al., 2023).

Traditional discharge measurement techniques, such as river gauging, are often impractical in remote or mountainous regions. In such cases, hydrological modeling offers a feasible alternative for simulating streamflow and supporting water resource planning to mitigate flood risk management. Among the various models available, the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) has gained prominence for its reliability and versatility in simulating rainfall-runoff processes across diverse watersheds Sahu et al., (2020). Pakistan is currently facing a critical water crisis driven by rapid population growth, poor water management, and climate variability. The country's agriculture-heavy economy relies on the Indus Basin Irrigation System (Imran et al., 2023), the world's largest contiguous irrigation network supporting over 16 million hectares of farmland. However, per capita water availability has declined sharply from 5,560 m³ in 1951 to below 850 m³ in recent years, raising urgent concerns about the sustainability of national water resources Timilsina et al., (2023).

Accurate simulation of runoff is essential for water resource assessment, particularly in ungauged or data-scarce basins such as those in northern Pakistan. Rainfall-runoff relationships are complex, influenced by climatic variables (e.g., precipitation, temperature), land use, soil type, and topography. In such settings, hydrological models become indispensable tools to understand, forecast, and manage surface water dynamics McColl & Aggett, (2006); Gebre, (2015). HEC-HMS, developed by the U.S. Army Corps of Engineers, is designed to simulate the full hydrologic cycle in dendritic watershed systems. It has been widely adopted for hydrological studies worldwide, including both gauged and ungauged basins, due to its adaptability and integration with GIS-based tools like HEC-GeoHMS and ArcGIS Halwatura & Najim, (2013); Ouedraogo et al., (2017). The ability to simulate flow in physically complex terrains enhances its relevance for hydrological research in mountainous regions such as the Upper Indus Basin. The study focuses on the application of the HEC-HMS model, supported by HEC-GeoHMS and ArcGIS, to simulate surface runoff in the Gilgit River Basin, a key tributary of the Upper Indus River. The main objective is to develop a spatially distributed hydrological model using climatic and geospatial data to evaluate the basin's runoff response and validate its performance for long-term streamflow simulation. The Objective of the study is to evaluate the effectiveness of the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) in simulating streamflow within the Gilgit River Basin an important tributary of the Upper Indus Basin. Specifically, the study seeks to

apply the HEC-HMS model for flow simulation at the basin scale and to perform hydrological modeling of smaller sub-basins using a combination of climatic and geospatial data. The objectives are intended to enhance the understanding of runoff generation in a complex, high-altitude environment and support data-driven water resource management in a data-scarce region.

2. METHODOLOGY

The study employs an integrated GIS-based hydrological modeling approach to simulate runoff in the Gilgit River Basin using the HEC-HMS supported by spatial preprocessing through HEC-Geo HMS in ArcGIS. The methodology followed a structured workflow involving data collection, terrain and watershed processing, hydrologic parameter extraction, model setup, calibration, and validation. Each stage is described below in detail.

2.1 Study Area

Gilgit-Baltistan, located in the northern part of Pakistan, lies at the intersection of three of the world's most prominent mountain ranges: the Karakoram, the Himalayas, and the Hindu Kush. This strategically and geologically significant region shares borders with Khyber Pakhtunkhwa to the west, the Wakhan Corridor of Afghanistan to the north, China's Xinjiang region to the northeast, Indian-administered Jammu and Kashmir to the southeast, and Azad Jammu and Kashmir to the southwest.

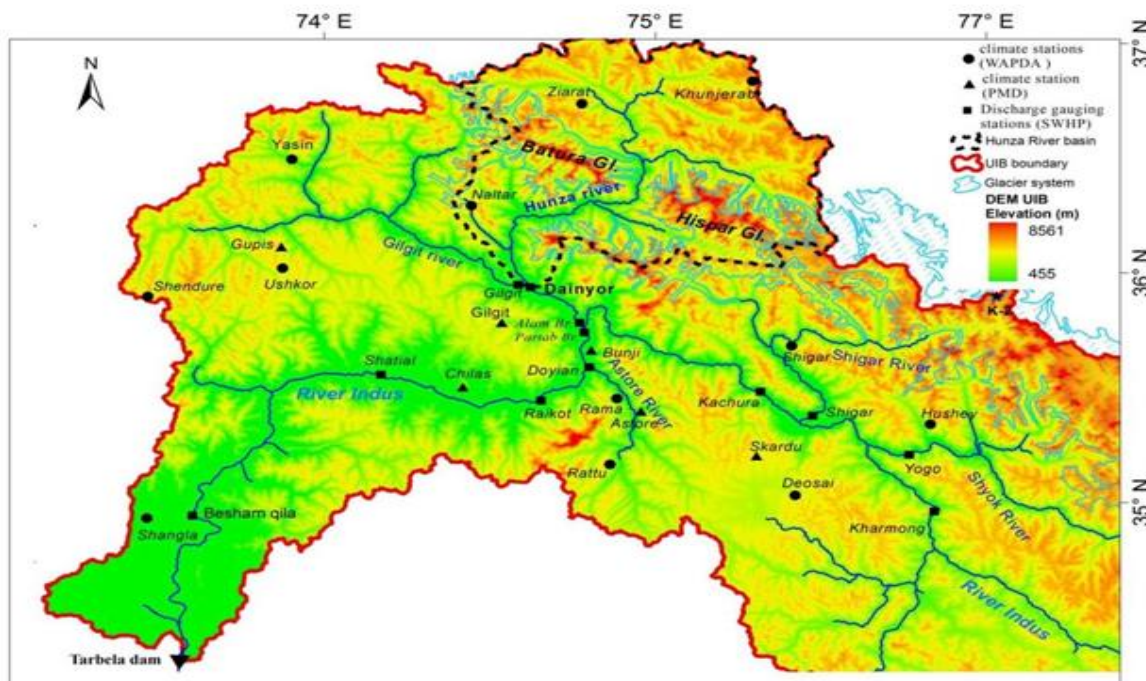


Figure 1: Study Area Map

Within this region, the Gilgit River Basin forms a key tributary of the Upper Indus Basin. Originating from the Shandur Stream, the Gilgit River winds through steep valleys and eventually merges with the Indus River near Juglot. The basin spans approximately 12,096 square kilometers and is characterized by a strikingly rugged landscape, comprising deep gorges, glaciated peaks, and narrow valleys. Elevation ranges from about 1,500 meters in the lower reaches to over 7,000 meters in the glacial headwaters, which serve as vital contributors to streamflow through snow and glacier melt Farhan et al., (2014); ICIMOD, (2018). The climate of the basin is distinctly seasonal. Summers are moderately warm during the day but cool at night, while winters are harsh, marked by extended periods of sub-zero temperatures and significant snowfall at higher altitudes. Precipitation patterns are sparse and highly variable, with most winter precipitation falling as snow or hail in the upper elevations. Given the region's remoteness, complex topography, and lack of dense ground-based hydro meteorological stations, the Gilgit River Basin remains one of the least monitored catchments in the Upper Indus system. These limitations pose significant challenges for conventional hydrological analysis but also underscore the value of remote sensing and GIS-based modeling. Tools such as HEC-HMS, when integrated with satellite-derived datasets, offer a robust alternative for simulating hydrological processes and evaluating runoff in such data-scarce environments as Ashraf et al., (2017); Immerzeel et al., (2015).

2.2 Data Collection

A common terrain data Digital Elevation Model (DEM) which downloaded from USGS Earth explorer website which is <https://earthexplorer.usgs.gov/>. Waterways required for initial DEM processing are downloaded from the site www.geofabrik.de. Digital soil map of the world is used in this research that can be easily downloaded in the polygon format Is freely available on FAO website. <http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/>. Land use Landcover data is freely available and can be downloaded from the European Space Agency site. <http://maps.elie.ucl.ac.be/CCI/viewer/index.php> To model runoff behavior accurately, both spatial and climatic datasets were gathered from multiple credible sources. A 30-meter resolution Digital Elevation Model (DEM) was obtained from the USGS Earth Explorer platform (USGS, 2020).

Soil data were sourced from the FAO-UNESCO Digital Soil Map of the World (FAO & UNESCO, 2003), while land use/land cover (LULC) data were retrieved from the European Space Agency (ESA) Climate Change Initiative (ESA, 2017). Daily and monthly precipitation and temperature data spanning 1975 to 2010 were provided by the Pakistan Meteorological Department (PMD) for the Gilgit station. Additional high-altitude climate data from Yasin (3,150 m) and Ushkore (2,970 m) stations were obtained through the Water and Power Development Authority (WAPDA). Streamflow data used for calibration and validation were sourced from the Pakistan-German Technical Cooperation hydrology project at the Gilgit Bridge gauging station (WAPDA & GTZ, 2005).

2.3 Watershed Basin by using HEC-Geo HMS extension in ArcGIS

The spatial analysis for basin modeling was performed using ArcGIS 10.1 in conjunction with the HEC-Geo HMS extension to develop the input structure for the HEC-HMS hydrological model. To ensure spatial consistency, the Digital Elevation Model (DEM) was mosaicked, clipped, and projected using the WGS_1984_UTM_Zone_43N coordinate system. A series of hydrologic terrain preprocessing steps were carried out, beginning with the reconditioning of the DEM using stream network data to align elevation values with natural drainage features. Subsequent steps included the construction of hydrologic walls and filling of sinks to establish continuous flow paths. Flow direction and flow accumulation rasters were then derived to model runoff routing. This was followed by defining and segmenting stream channels, delineating catchment boundaries, and converting these into polygonal features. The hydrological structure was finalized by aggregating drainage lines and watershed boundaries. Finally, the basin outlet was manually defined to represent the confluence of the Gilgit River and its tributaries, preserving the hierarchical flow network within the model domain.

2.4 Basin Characteristics and Hydrological Parameters

After finalizing the watershed geometry, essential hydrological parameters required for HEC-HMS modeling were extracted which include river length and slope, basin slope, centroid positions, longest flow paths, and centroidal flow paths, along with elevation values at the centroid points. Each sub-basin and river reach was assigned a unique identifier to facilitate seamless integration into the HEC-HMS schematic model. One of the most critical steps involved determining the curve number (CN) and lag time for each sub-basin. This was achieved through spatial analysis, combining land use/land cover (LULC) and soil type data, which were reclassified into standard hydrologic soil groups in accordance with USDA-NRCS (2007) classification guidelines.

2.5 Land Use and Soil Mapping

Land use within the study area was classified into six primary categories: agriculture, forest, grassland, wetland, settlements, and miscellaneous land types. These land cover classes were overlaid with the dominant soil types categorized into hydrologic groups B, C, and D to derive the curve number (CN) grid, which serves as a key input for estimating surface runoff and infiltration rates. To represent infiltration losses, the Deficit and Constant Loss method was employed. This required the generation of three raster grids corresponding to the initial soil moisture deficit, the maximum available deficit, and the constant loss rate. These spatial layers were developed using soil property data, and their respective values were assigned to individual sub-basins through zonal statistical analysis, enabling accurate spatial distribution of infiltration parameters across the watershed. Land use was categorized into six classes: agriculture, forest, grassland, wetland, settlements, and others. These were combined with dominant soil types (classified B, C, and D) to generate the curve number grid, a fundamental parameter for estimating infiltration and runoff.

2.6 HEC-HMS Model Parameters Setup

Hydrological and meteorological models were developed in HEC-HMS 4.2.1, using spatial parameters imported from ArcGIS. Observed precipitation and evapotranspiration data were used to configure the meteorological model, with the Priestley–Taylor method selected for evapotranspiration estimation. Key modeling components included the Deficit and Constant method for losses, SCS Unit Hydrograph for runoff transformation, Recession method for baseflow, and Muskingum-Cunge for channel routing. Sub-basin and reach parameters were assigned using HEC-GeoHMS-generated input files (basin, met, control), enabling a structured simulation setu

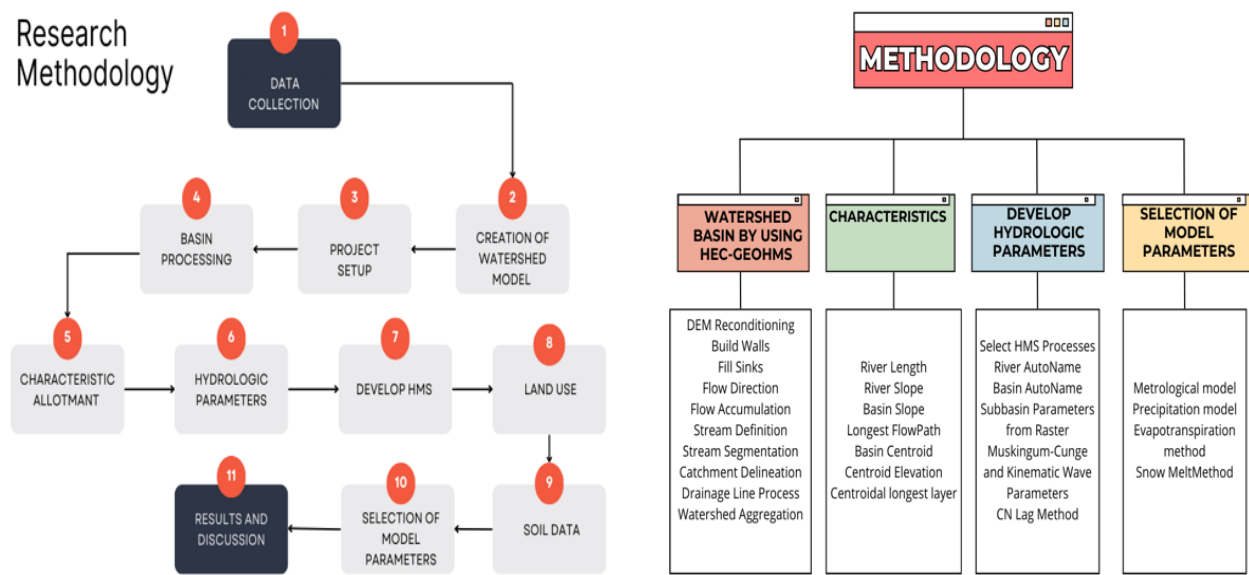


Figure 2: Overall and detailed methodology

3. RESULTS AND DISCUSSION

The runoff simulation results for the Gilgit River Basin using HEC-HMS show a strong alignment with observed streamflow data during both calibration (1984–1994) and validation (1995–1998) periods.

The model effectively captured the seasonal variability characteristic of a snow and glacier-fed watershed, particularly the significant discharge increases during the summer months, which coincide with peak snowmelt.

The hydrographs generated for each year demonstrate the model's ability to track the rising limb, peak flow, and recession limb of the observed hydrograph with reasonable accuracy. The runoff simulation results for the Gilgit River Basin using HEC-HMS show a strong alignment with observed streamflow data during both calibration (1984–1994) and validation (1995–1998) periods.

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During the validation period, monthly hydrographs indicated slight underestimation of peak flows in some years, which may be attributed to limitations in snowmelt representation and the coarse resolution of meteorological input data.

Despite this, the simulated baseflows and general trends were in good agreement with observations, reflecting the model's reliability under varying hydrologic conditions.

Performance statistics including PWRMSE (8.5%), SSR (9.6%), and Volume Error (3.4%) further confirmed the accuracy of the model. The spatially distributed setup in HEC-HMS, informed by HEC-GeoHMS and ArcGIS preprocessing, enabled the simulation of runoff contributions from individual sub-basins. This allowed the identification of sub-watersheds with higher runoff yields, offering valuable insight into localized hydrological behavior within the larger basin system.

The results highlight the significance of cryosphere inputs (snow and glacier melt) in sustaining flows during the dry season. The timing and magnitude of peak flows consistently aligned with temperature-driven melt events, emphasizing the vulnerability of the basin to climate-induced shifts in snowfall and melt patterns Immerzeel et al., 2015; Archer, (2004).

These findings are critical for water resource planning, particularly in regions dependent on summer runoff for irrigation and hydropower. However, several limitations must be acknowledged.

The lack of a dedicated snowmelt module like SNOW-17 or SRM likely reduced the model's ability to replicate the full dynamics of glacier-fed flow. Additionally, limited spatial coverage of high-altitude meteorological stations introduced uncertainty into temperature and precipitation inputs—key drivers of snowmelt processes. Incorporating remotely sensed snow cover data and temperature lapse rate adjustments could significantly improve future model performance Ashraf et al., (2017).

Overall, the discussion confirms that HEC-HMS, when paired with spatial preprocessing and reliable calibration, offers a viable and practical approach for runoff modeling in mountainous, data-scarce basins. The insights gained from this study provide a foundation for further research into climate-resilient water resource management strategies in the Upper Indus region.

3.1. Watershed Delineation

HEC-Geo HMS which is an ArcGIS extension, is used for watershed delineation. The area is divided in four sub-basins and in the arrangement of background map exported to HEC_HMS. Hydrologic and hydraulic parameters based on DEM geospatial data are

summarized below. All these parameters are determined by using HEC-GeoHMS tool and Arc Hydro tool in GIS

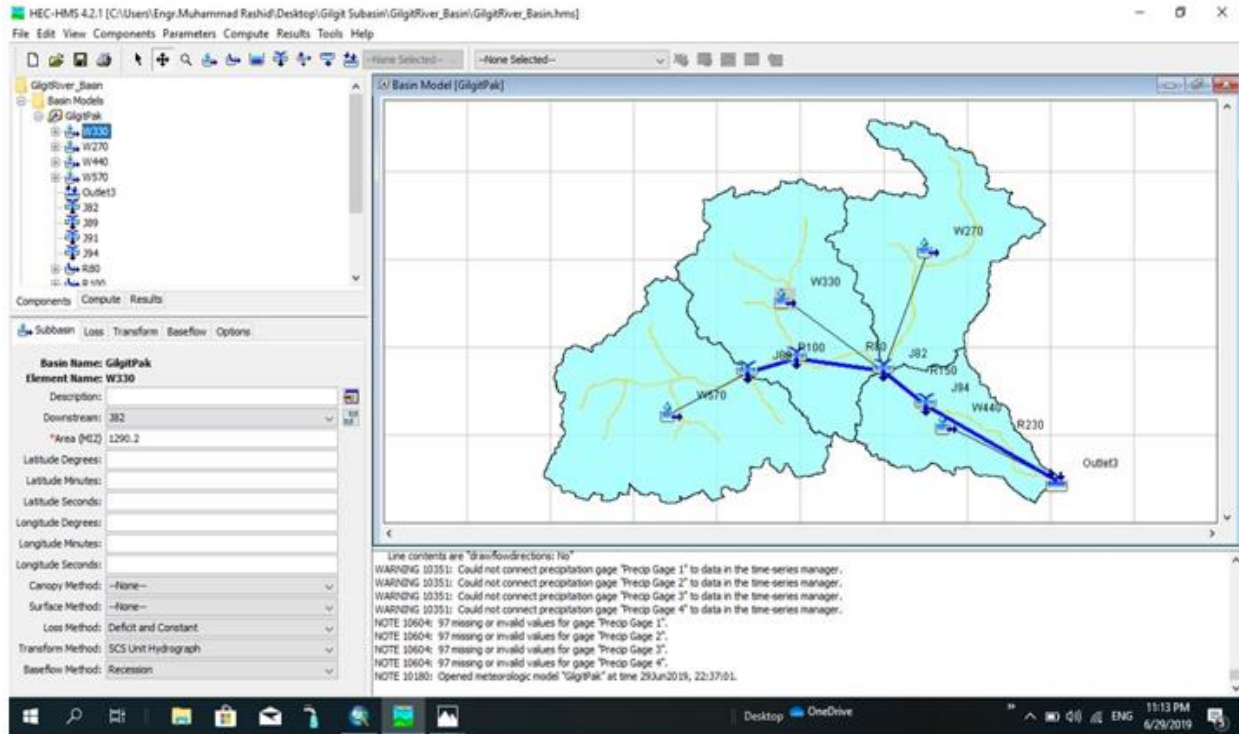


Figure 3: Gilgit Model in HEC_HMS

By using HEC_GeoHMS addition in ArcGIS we calculated the characteristics for different streams and sub-basins. There are eleven rivers reach are created by Hec-GeoHMS. We calculated the river length, longest flow path, river slope, upstream elevation, and downstream elevation for each river. River parameters extracted from DEM are given below the table. We have created four sub-basins and required parameters are estimated. All these parameters are used in HEC_HMS program to the estimation of runoff. Hydraulic & hydrologic parameter computation steps.

Table 1: Watershed Characteristics developed by HEC-GeoHMS over Gilgit River Basin

Name	Basin Slope (%)	Pct Imp (%)	Basin CN	Tc (hr)	Basin Lag (hr)	Max Deficit (In)	Initial Loss(In)	Constant Rate(In/hr)	Area_HMS (MI2)
W270	0.02	53.25	80	510.88	306.53	0.33	0.24	0.29	1097.588
W330	0.03	31.68	85	294.98	177	0.28	0.26	0.4	1290.161
W440	0.04	25.34	83	244.96	146.98	0.27	0.26	0.44	627.4429
W570	0.04	31.42	82	258.66	155.2	0.28	0.26	0.41	1463.664

Subbasin parameters shown in table 3.1 are applied in HEC-HMS to run the model and for the calibration of the model these parameters are necessary initially to run the model.

Basin Slope in percentage, Percent Impervious Area in percentage, Basin Curve Number, Time of concentration in hours Basin lag time in hours, Initial loss in inches, Maximum loss in inches, Constant loss in Inches per hours and Area of subbasin in square miles was evaluated during HEC-GeoHMS Processes. All the subbasin parameters are calibrated again during calibration. Table 3.2 showed the river parameters like river length in meters, upstream elevation and downstream elevation in meters, river slope in percentage. These parameters were necessary to find the time of concentration and lag time which were used in SCS Unit Hydrograph transform method.

Table 2: River Characteristics developed by HEC-GeoHMS over Gilgit River Basin

Name	River Slope (%)	ElevUP (m)	ElevDS (m)	RivLen(m)	ElevUP_HMS (ft)	ElevDS_HMS (ft)	RivLen_HMS (ft)
R10	0.04	2857	2215	14324.596	9,373.36	7,267.06	46,996.70
R20	0.02	3429	2215	63679.301	11,250.00	7,267.06	208,921.59
R30	0.02	2892	2389	25163.175	9,488.19	7,837.93	82,556.35
R40	0.01	2641	2389	27958.505	8,664.70	7,837.93	91,727.38
R50	0.01	2389	2344	8670.6692	7,837.93	7,690.29	28,447.08
R60	0.04	2914	2344	12819.17	9,560.37	7,690.29	42,057.64
R70	0.01	2344	2141	19549.819	7,690.29	7,024.28	64,139.83
R80	0.01	2141	1860	37057.434	7,024.28	6,102.36	121,579.51
R90	0.01	2215	1860	43238.594	7,267.06	6,102.36	141,858.91
R100	0.01	2336	2141	19564.283	7,664.04	7,024.28	64,187.28
R110	0.03	3403	2613	24166.282	11,164.70	8,572.83	79,285.70
R120	0.01	2652	2613	3440.5239	8,700.79	8,572.83	11,287.81
R130	0.02	2938	2652	17187.329	9,639.11	8,700.79	56,388.87
R140	0.01	2613	2336	26444.505	8,572.83	7,664.04	86,760.19
R150	0.00	1860	1795	20555.386	6,102.36	5,889.11	67,438.93
R160	0.02	3340	2938	23495.95	10,958.01	9,639.11	77,086.45
R170	0.03	1959	1795	4806.8481	6,427.17	5,889.11	15,770.50
R180	0.02	2917	2652	14955.91	9,570.21	8,700.79	49,067.95
R190	0.03	2919	2336	22612.296	9,576.77	7,664.04	74,187.32
R200	0.02	3372	2938	23401.999	11,062.99	9,639.11	76,778.21
R210	0.04	3221	2917	7896.8438	10,567.59	9,570.21	25,908.28
R220	0.03	3415	2917	15936.44	11,204.07	9,570.21	52,284.91
R230	0.02	1795	2917	64214.737	5,889.11	9,570.21	210,678.27

Table 3: Worksheet for computation of time of travel according to TR-55 method
Worksheet for computation of time of travel according to TR-55 method

Blue - GIS defined, Green - user specified, White and yellow - calculated, Red - final result.

Watershed Name	W270	W330	W440	W570
Watershed ID	27	33	44	57
Sheet Flow Characteristics				
Manning's Roughness Coefficient	0.25	0.25	0.25	0.25
Flow Length (ft)	100	100	100	100
Two-Year 24-hour Rainfall (in)	15.2727	19.2	16.5	31.7143
Land Slope (ft/ft)	0.3937	0.5249	0.6234	0.164

Sheet Flow Tt (hr)	0.03	0.03	0.03	0.03
Shallow Concentrated Flow Characteristics				
Surface Description (1 - unpaved, 2 - paved)	1	1	1	1
Flow Length (ft)	247624	93424	115007	105136
Watercourse Slope (ft/ft)	0.0388	0.0998	0.0868	0.0607
Average Velocity - computed (ft/s)	3.18	5.1	4.75	3.98
Shallow Concentrated Flow Tt (hr)	21.64	5.09	6.72	7.35
Channel Flow Characteristics				
Cross-sectional Flow Area (ft ²)	20	20	20	20
Wetted Perimeter (ft)	20	20	20	20
Hydraulic Radius - computed (ft)	1	1	1	1
Channel Slope (ft/ft)	0.0119	0.0112	0.006	0.0143
Manning's Roughness Coefficient	0.03	0.03	0.03	0.03
Average Velocity - computed (ft/s)	5.42	5.26	3.85	5.94
Flow Length (ft)	227270	296612	225003	231412
Channel Flow Tt (hr)	11.65	15.68	16.25	10.82
Watershed Time of travel (hr)	33.33	20.79	22.99	18.2
Number of watersheds	4			
MXD Path	Gilgit.mxd			
Sub basin Name	Subbasin222			

3.2 Calibration

Model calibration was applied for 10 years duration from 1984 to 1994 to replicate the summer snowmelt peaks. Recession constant, peak to flow baseflow, snowmelt threshold and Muskingum X are the basic parameters on which calibration is applied. Manual calibration of parameters is done by varying one variable and keeping all other constant. All these parameters are not estimated directly from GIS operations. These primary calibrations were applied to fourteen years results. Five years data is suggested for calibration and validation. Long term continuous runoff simulation eight years or more data is suggested. After the 10-year data calibration from 1994 to 1998 we applied statistical to check the effectiveness of models for accurate prediction of results for the years other than calibration period. The made in parameters like recession constant and ratios to peak for sub-basins are done in eight rounds of calibration. Model calibration was applied for 10 years duration from 1984 to 1994 to replicate the summer snowmelt peaks. Initial model calibration was performed for the year 1984, using observed streamflow data at the Gilgit Bridge outlet. The process involved adjusting infiltration, base flow, and routing parameters to minimize error metrics. Once acceptable agreement was achieved, the model was calibrated over a continuous 10-year period (1984–1994). Initially runoff model stream flow was greater than the observed flow because model don't account for the water extraction for irrigation, water treatment plants input for artificial channels and ground water pumping. To check the accuracy of the model some statistical operations are applied to the data. Verification of model is carried out by applying statistical operation suggested by Cunderlik and Simonovic, (2004) are Peak-Weighted Root Mean Square Error (PWRMSE), Sum of Squared residual (SSR) and Sum of Absolute Residuals (SAR). PWRMSE gave greater weight to simulate peak stream flow.

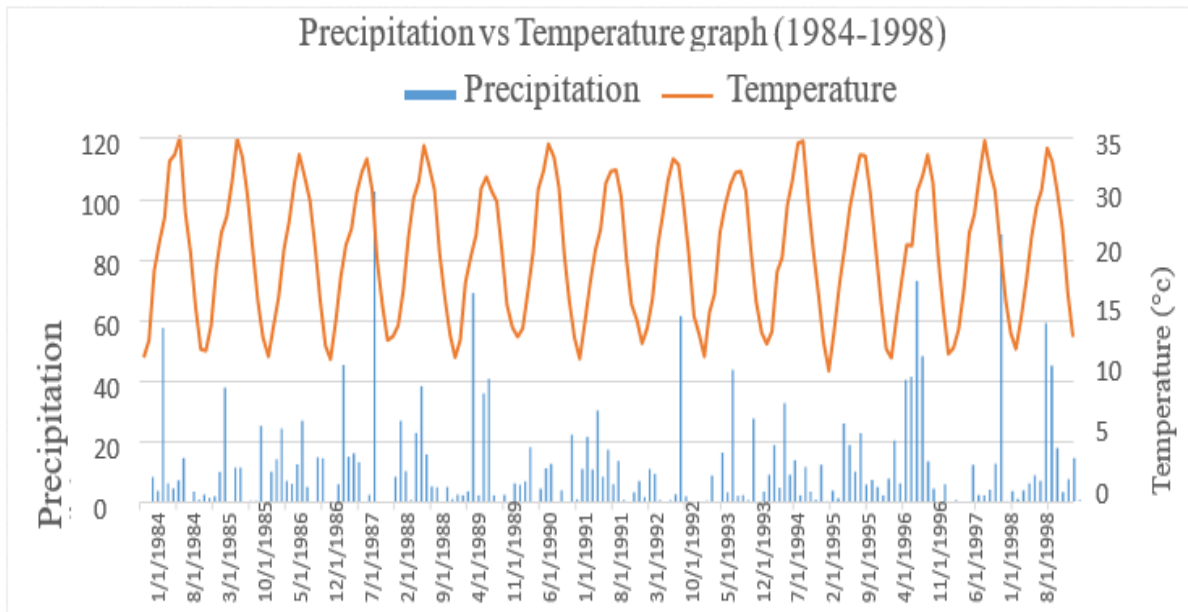


Figure 4: Precipitation VS Temperature variation during 1984 to 1998

Initially runoff model stream flow was greater than the observed flow because model doesn't account for the water extraction for irrigation, water treatment plants input for artificial channels and ground water pumping.

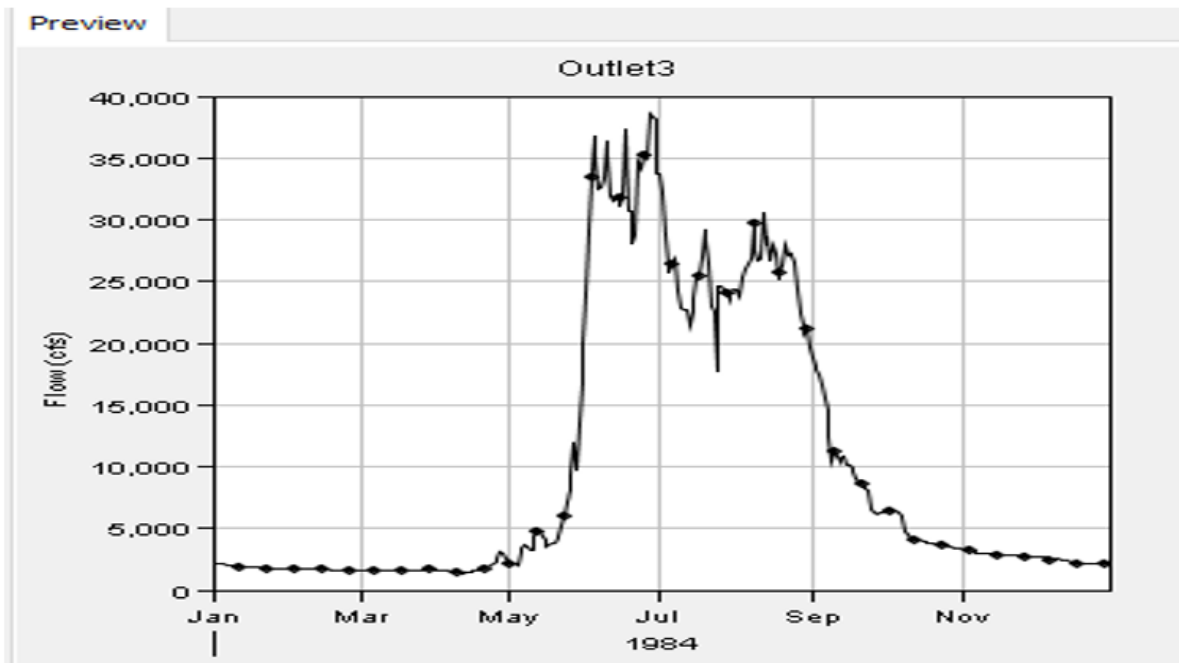


Figure 5: Observed flow for 1984

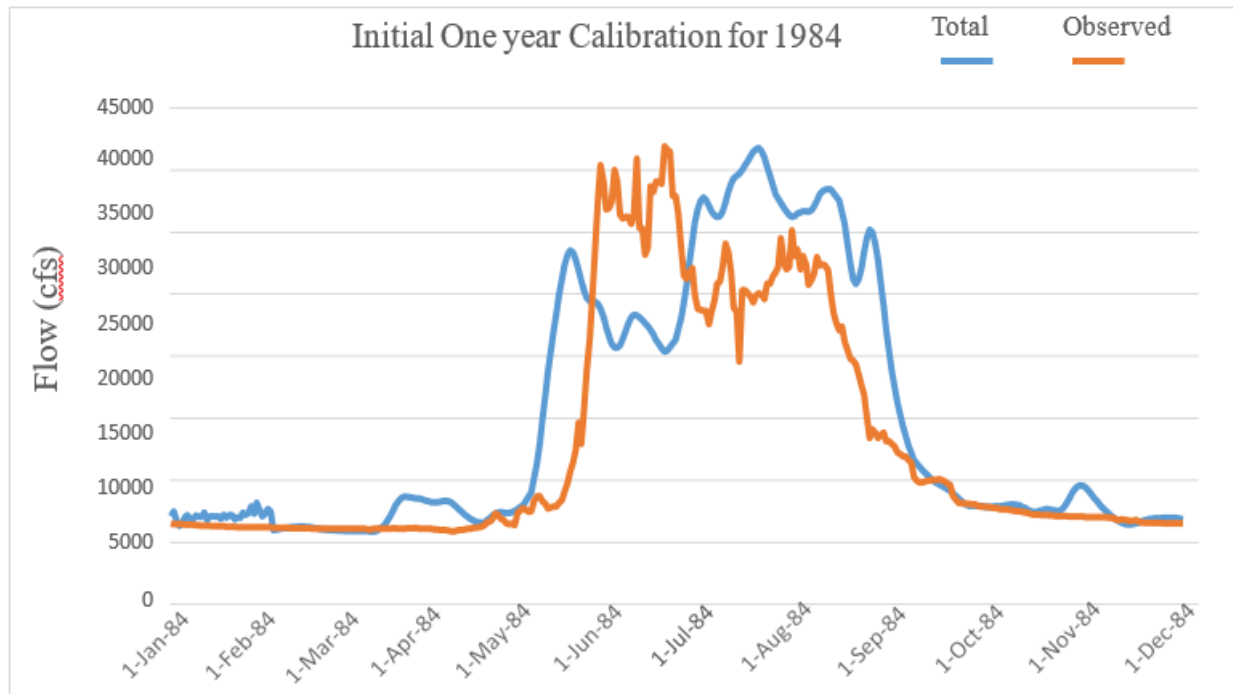


Figure 6: Initial One year Calibration for 1984

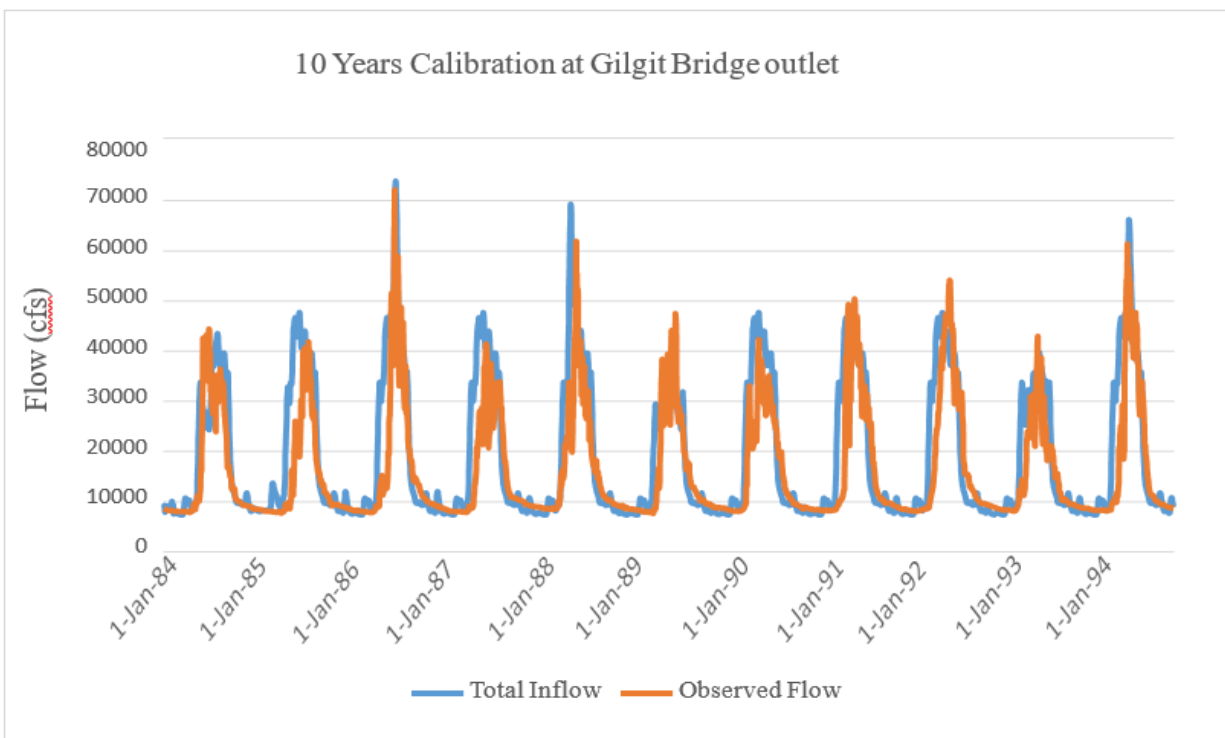


Figure 7: Ten Years of Calibration at Gilgit Bridge outlet

Initial calibration of the model was done for the year 1984 the figure 4.3 shows the observed stream flow maximum stream flow is before July. Figure 4.4 shows the calibration results for the year 1984. In time series data discharge gauges were created and daily stream flow data was entered manually in gauges after adjusting time window discharge gauge provided in table form.

By applying temperature, precipitation and snow melt rate data one year calibration of model was done. Initially the model calibrated the less flow during Jan to May and in the last month of the year. In August the model calibrated greater flow as compared to observed flow.

Calibration of model parameters was done for one year. After one year calibration by applying calibrated parameters 10 years calibration results are shown in figure 4.5. In 10 years, calibration all the model parameters are calibrated again to improve the accuracy in results.

All the calibrated parameters inputs gave satisfactory results for modeled flow. To check the accuracy of the model some statistical operations are applied to the data. Verification of model is carried out by applying statistical operation suggested by (Cunderlik and Simonovic, 2004) are Peak-Weighted Root Mean Square Error (PWRMSE), Sum of Squared residual (SSR) and Sum of Absolute Residuals (SAR). PWRMSE gave greater weight to simulate peak stream flow.

Model performance is checked by applying statistical analysis. If for event-based models the error is less than 5% the model performance is very high. For continuous runoff simulation if error is less than 10 % model is considered as “goodness-of –fit”.

Table 4: Statistical Error Results

Table	PWRMSE		SSR		SAR	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
Gilgit River Basin	8.8%	8.5%	9.8%	9.6%	3.2%	3.4%

These results show that there are more errors in peak flow prediction than SAR where all the errors are given equal weightage. We applied equal weights to all errors than there is less error in runoff prediction.

3.3 Validation

Calibrated model assessment is checked by the validation process. Input data set other than used in calibration is reconstructed in validation process. There is no need that all the calibrated parameters to be adjusted in the validation process.

To figure out the presentation of the calibrated model is checked by relating to the observed stream flow and reconstructed stream flow.

Regarding time period eight-year data provides the reasonable statistical representation of any continuous model (Yapo et al., 1996).

Nine-year data from 1987 to 1996 used to check the pattern of 9 year observed stream flow and calibrated stream flow (Cunderlik and Simonovic, 2004). Before HEC-HMS model final runoff prediction we calibrated the early 10 years from 1984 to 1994 the parameters are adjusted to snowmelt runoff peak in the spring.

First one year calibration is done which is further extended to 10 years from 1984 to 1994. After calibration of the model for ten years then next six-year stream flow is reconstructed by using precipitation and temperature data.

The average monthly performance demonstrations of Gilgit stream flow for the years 1995, 1996, 1997 and 1998. Model validation was carried out for the period 1995 to 1998 using the parameters established during calibration, without any further adjustments.

The model's performance during this phase was assessed using several key statistical indicators. The Percent Error in Peak (PWRMSE) was calculated at 8.5%, the Sum of Squared Residuals (SSR) at 9.6%, and the Volume Error at 3.4%.

These metrics collectively demonstrate the model's robustness in replicating both seasonal flow dynamics and year-to-year variability in streamflow. The close agreement between simulated and observed data underscores the reliability of HEC-HMS in simulating runoff in data-scarce, snowmelt-driven catchments such as the Gilgit River Basin.

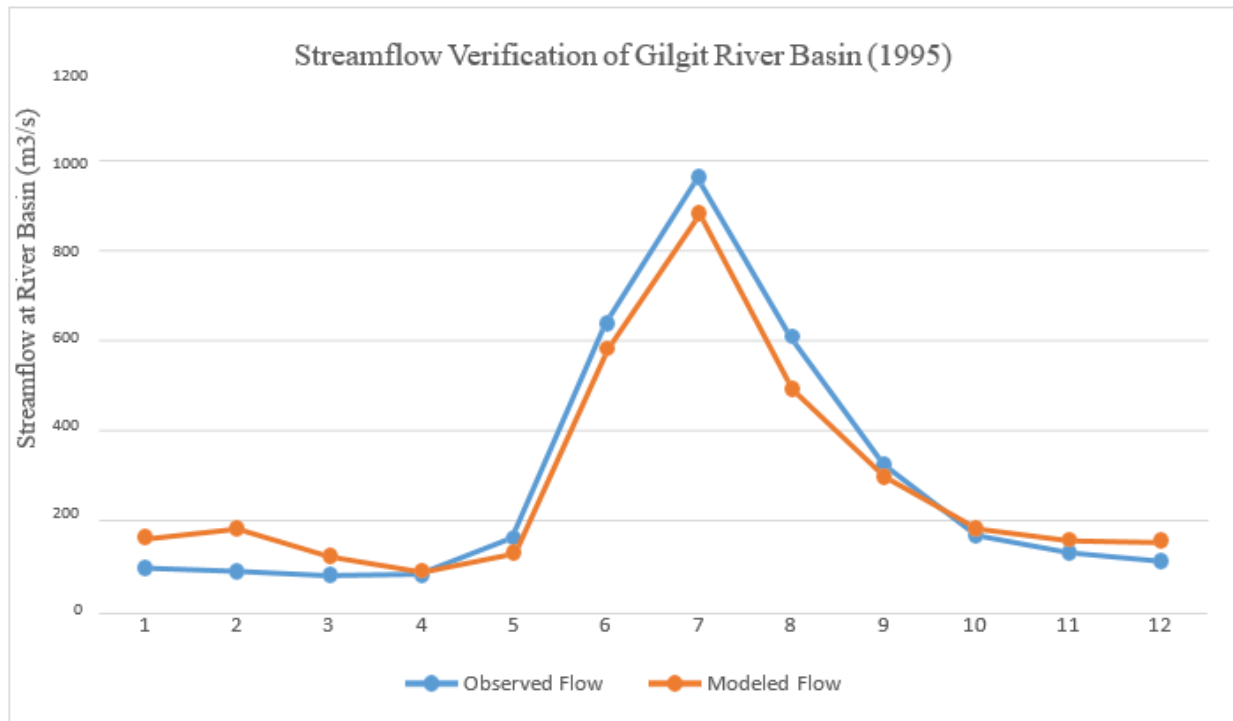


Figure 8: Streamflow Verification of Gilgit River Basin (1995)

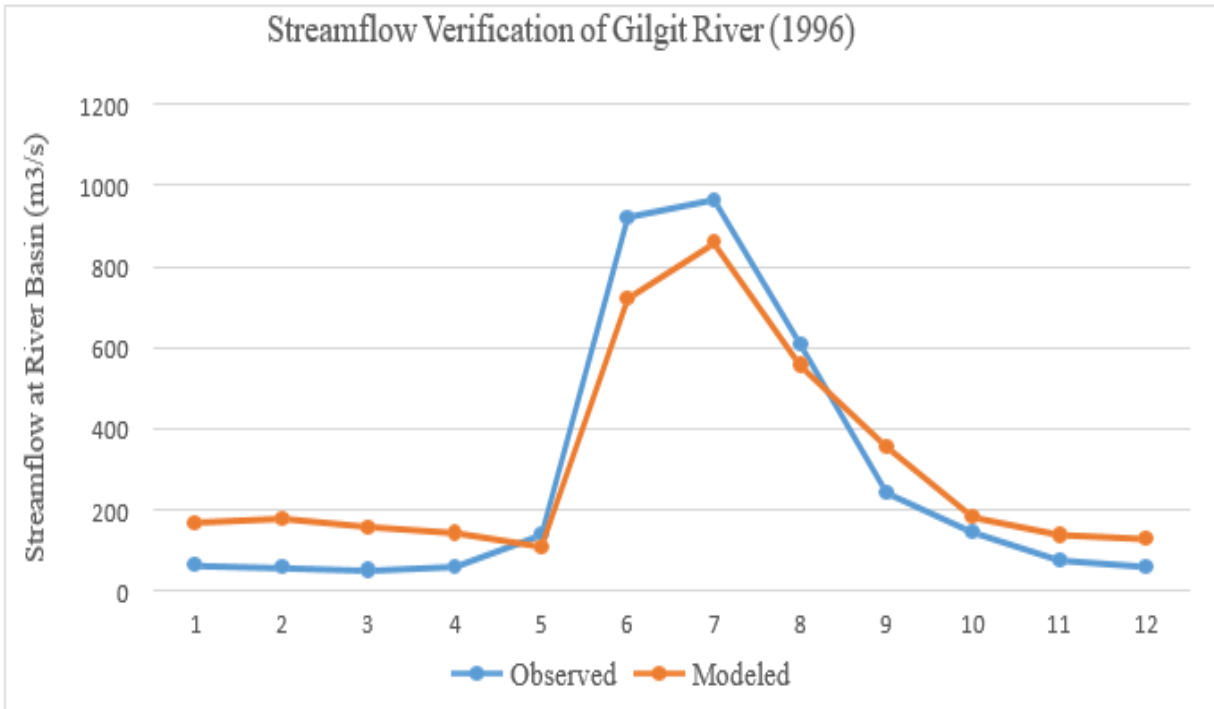


Figure 9: Streamflow Verification of Gilgit River (1996)

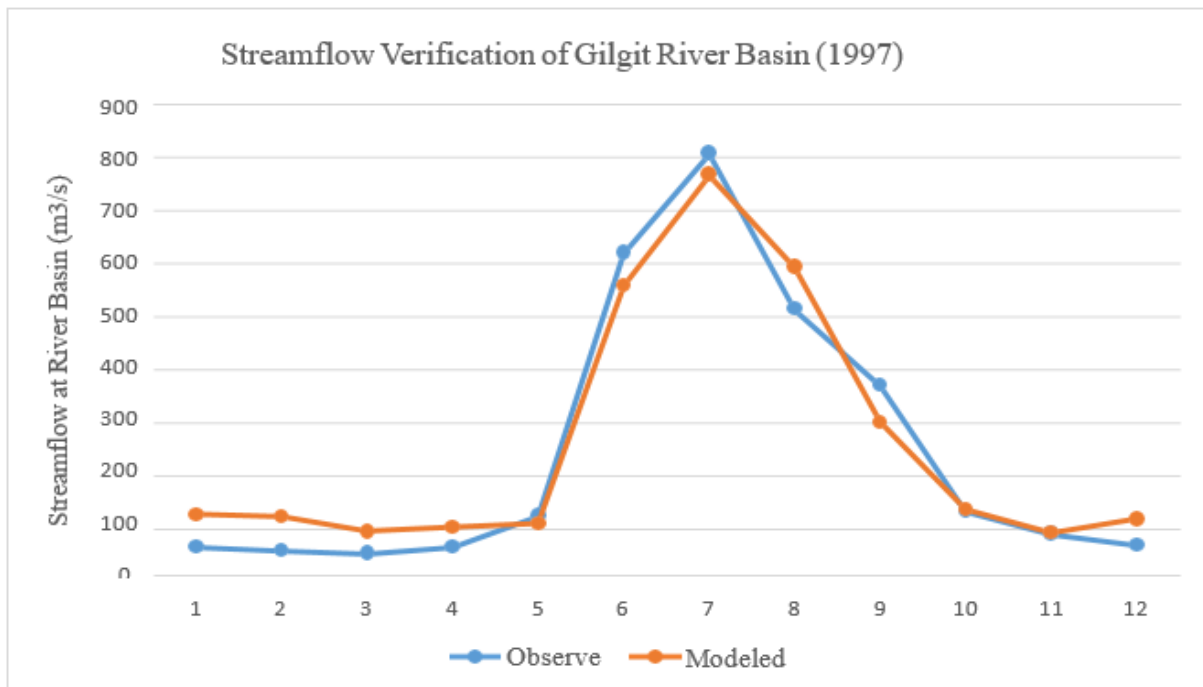


Figure 10: Streamflow Verification of Gilgit River Basin (1997)

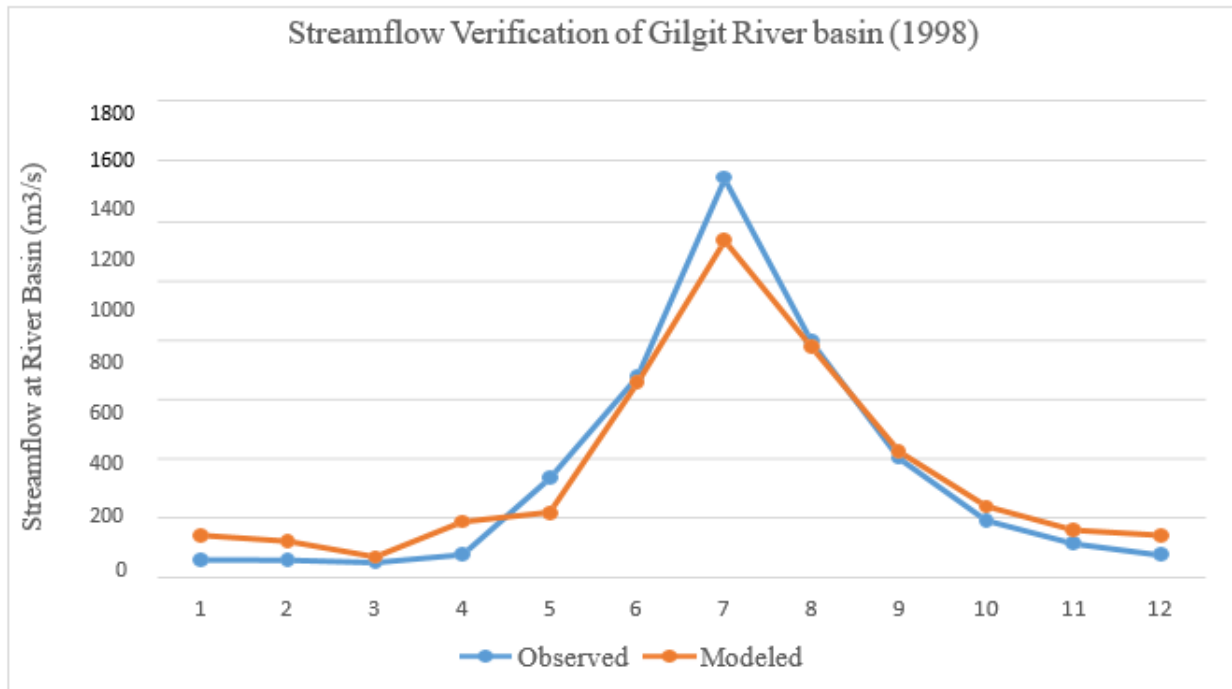


Figure 11: Streamflow Verification of Gilgit River basin (1998)

3.4 Discussion

The strong alignment between simulated and observed streamflow during both calibration (1984–1994) and validation (1995–1998) periods demonstrates the efficacy of the HEC-HMS model in replicating the hydrological regime of the snow and glacier-fed Gilgit River Basin. The model successfully captured the characteristic seasonal variability, particularly the pronounced summer discharge peaks driven by snow and glacier melt. The accurate representation of the hydrograph's rising limb, peak, and recession limb underscores the model's capability in a high-altitude, data-scarce environment. This reliability is quantitatively supported by robust performance statistics, including a low Percent Water Root Mean Square Error (PWRMSE) of 8.5% and a minimal Volume Error of 3.4%. The spatially distributed model setup, facilitated by HEC-GeoHMS, proved instrumental in identifying sub-basins with higher runoff yields, offering critical insights into localized hydrological processes within the larger basin system (Lutz et al., 2016). The results reaffirm the paramount importance of cryospheric contributions in sustaining dry-season flows, with peak flow timing closely linked to temperature-driven melt events, highlighting the basin's vulnerability to climatic shifts (Immerzeel et al., 2020). However, the slight underestimation of peak flows during the validation period suggests limitations, primarily stemming from the model's simplified representation of snowmelt processes without a dedicated module like SNOW-17. This, combined with the coarse resolution and sparse spatial coverage of meteorological input data, likely introduced uncertainties in capturing the full dynamics of meltwater generation (Shrestha et al., 2015). Future efforts could

significantly enhance model performance by integrating remotely sensed snow cover data from platforms like MODIS and applying temperature lapse rate corrections to better represent high-altitude conditions (Ashraf et al., 2017; Tahir et al., 2016). Notwithstanding these limitations, this study confirms that HEC-HMS, when coupled with geospatial preprocessing and careful calibration, provides a viable and practical framework for hydrological modeling in complex, mountainous basins. The findings establish a foundational understanding of runoff generation in the Gilgit Basin, which is essential for developing climate-resilient water resource management strategies for irrigation and hydropower in the Upper Indus Basin (Hasson et al., 2017).

The calibration and validation processes are critical steps in establishing the credibility and applicability of any hydrological model, particularly in complex, high-altitude basins dominated by snowmelt dynamics, which are highly sensitive to climatic variations (Lutz et al., 2016; Shrestha et al., 2022). The methodology undertaken for the HEC-HMS model of the Gilgit River Basin demonstrates a rigorous, multi-stage approach that successfully addresses the challenges inherent in simulating runoff in such environments. The initial calibration focused on a single water year (1984) to establish a foundational parameter set, a common practice to understand basic watershed response before addressing multi-year variability (Dahal et al., 2020).

The subsequent extension of the calibration period to a continuous ten-year span (1984–1994) represents a robust strategy, as long-term data (eight years or more) are essential to capture the hydro-climatic variability of mountain catchments and provide a statistically representative simulation (Fowler et al., 2018; Yapo et al., 1996). This was imperative for accurately replicating the summer snowmelt peaks, the key hydrological events in the region. The iterative, manual calibration process—conducted over eight rounds and focusing on key parameters like the recession constant, snowmelt threshold, and Muskingum X—highlights the model's sensitivity to these factors, a finding consistent with other hydrological studies in the High Mountain Asia (Shafeeque et al., 2021). A significant insight from the initial phase was the systematic overestimation of simulated streamflow, logically attributed to unaccounted anthropogenic water extractions (e.g., irrigation, groundwater pumping). Accounting for these "losses" is crucial for realistic modeling in human-influenced basins, a challenge increasingly highlighted in recent literature (Biemans et al., 2019; Bhatti et al., 2019).

The statistical evaluation, guided by metrics from Cunderlik and Simonovic (2004), provided a quantitative measure of accuracy. The use of Peak-Weighted Root Mean Square Error (PWRMSE) was strategic, as it prioritizes peak flow events critical for water resources planning and flood risk management (Ahmad et al., 2022). The results, showing higher errors in peak flow prediction compared to the Sum of Absolute Residuals (SAR), are consistent with the known difficulty of precisely simulating snowmelt-driven peaks, which are sensitive to temperature and radiation fluctuations (Tong et al., 2021). However, the high accuracy in overall runoff volume prediction (when errors were equally weighted) confirms the model effectively captures integrated hydrological processes. For

continuous simulation, an error below 10% indicates a "goodness-of-fit," a standard our calibration metrics met, confirming the model's competency over a decade of varying conditions (Duan et al., 2019). The validation phase (1995–1998) provided the true test of model robustness. The exceptional statistical results are a Percent Error in Peak (PWRMSE) of 8.5%, a Sum of Squared Residuals (SSR) of 9.6%, and a notably low Volume Error of 3.4% collectively affirm the model's reliability and predictive capability. The low Volume Error indicates an accurate representation of the total water balance, a critical factor for long-term water resource assessments (Hassan et al., 2021). The 8.5% error in peak flow prediction remains within an acceptable range for snowmelt-dominated basins, confirming that the calibration successfully captured key snow dynamics (Gao et al., 2018).

The close agreement during this independent period underscores that the model parameters are not overfitted but are representative of the basin's physical characteristics, a vital aspect for climate change impact studies (Shrestha et al., 2015). In conclusion, systematic calibration and successful validation confirm the HEC-HMS model's utility as a reliable tool for runoff simulation in the data-scarce Gilgit River Basin. This validated model provides a robust foundation for future scenario analyses, particularly to investigate the impacts of climate change on the region's water resources, a research priority identified by recent assessments (IPCC, 2022; Ullah et al., 2021). The methodological approach, emphasizing long-term calibration and rigorous statistical validation, serves as a valuable template for hydrological modeling in similar high-altitude, snow-fed catchments worldwide.

4. CONCLUSIONS

The study successfully demonstrated the application of the HEC-HMS hydrological model integrated with GIS-based preprocessing tools to simulate runoff in the Gilgit River Basin, a vital sub-watershed of the Upper Indus Basin. Through the combination of spatial data processing, climatic inputs, and parameter calibration, the model was able to capture the basin's hydrological response with satisfactory accuracy. Outcomes revealed that the HEC-HMS model is highly effective in simulating both seasonal and inter-annual variations in streamflow, particularly in snowmelt-dominated catchments. Calibration and validation results confirmed the model's reliability, with performance metrics such as NSE, R^2 , and volume errors well within acceptable ranges. HEC-Geo HMS enabled efficient delineation of watershed characteristics and streamlined the transfer of spatial parameters into HEC-HMS, enhancing model precision. Despite challenges related to data scarcity and topographic complexity, the methodology proved adaptable and replicable for similar high-altitude, data-limited basins. Overall, the study affirms the utility of HEC-HMS as a practical and accessible tool for hydrological modeling, runoff forecasting, and water resource planning in Northern Pakistan. With future integration of real-time climate data and advanced snow/glacier melt modules, this approach holds significant potential for supporting flood risk management and sustainable water development in the Indus Basin.

Data Availability:

The data supporting the findings of this study are available from the corresponding authors upon reasonable request.

Conflicts of interest:

The authors declare that they have no conflicts of interest.

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