# ENSEMBLING CLIMATE VARIATIONS FOR STREAMFLOW PREDICTION USING GIS BASED STANDARD RAINFALL-RUNOFF MODELS IN CRYOSPHERE CATCHMENTS

## FINAL YEAR PROJECT UG 2012

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## ABSTRACT

Investigation of continuous daily streamflow of high altitude cryosphere catchment based mainly on both snowmelt- and rainfall-runoff, is particularly challenging in case of limited climatic records. The aim of this study is to compare the accuracy of two different rainfall runoff hydrological models, SWAT (Soil and Water Assessment Tool) and HBV (Hydrologiska Byråns Vattenbalansavdelning model) through performance of continuous simulation of snowmelt and rainfall runoff in Gilgit River basin, northern Pakistan under current and potential climate-change scenarios. We used European Centre for Medium Range Weather Forecasts, ERA Interim (ECMWF) daily temperature, precipitation, evapotranspiration data and Coupled Model Intercomparison Project (CMIP3) daily Solar Radiation, Relative Humidity and Wind Speed datasets to examine the efficiency of both models. The observed streamflow data of thirteen years (1990–2002) was used for the calibration and five years (2003 – 2007) data for validation of models. A good agreement was attended between simulated and observed streamflows for annual snowmelt season in the calibration and validation period (0.93, 0.23) and (0.75, 26.30) for HBV and (0.60, 34.26) and (0.74, 10.73) for SWAT [statistic are (Nash-Sutcliffe efficiency and difference in volume %)], respectively. For potential climate-change scenarios, streamflow was projected using different precipitation and temperature scenarios. For temperature variations of -2 – +4°C HBV and SWAT showed a variation in annual streamflows of -16.92% – 6.6% and -28.71% – 2.96% respectively. While change in precipitation of -10% – +20% showed a variation of -6.65% – 13.3% and -18.13% – 27.5% in HBV and SWAT respectively. End results of the project reveal that HBV has higher efficiency and requires less datasets than SWAT to accurately predict rainfall using Remotely Sensed data. Also, HBV shows more consistent results of streamflow under changing climate conditions in Gilgit basin.

**Keywords:** Hydrologic modeling; Climate change; Runoff simulation; SWAT; HBV

# TABLE OF CONTENTS

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

# LIST OF FIGURES

# LIST OF TABLES

# CHAPTER 1

# INTRODUCTION

## 1.1 General

The economy of Pakistan is to a great extent reliant on hydrological assets for agribusiness and power generation. Majority of the water needs for these industries come from the precipitation that falls as snow on the mountain peaks and start melting in early summer period to give us significant amount of discharge. Scientific community has been working to forecast the potential discharge from these frozen reservoirs either by forming new hydrological models (Ohara et al. 2010; Şensoy 2005) or by testing the accuracies of these models in different parts of the world.

There are two main approaches for estimation of the snowmelt either by energy balance approach or by using temperature degree-day method. Energy balance approach uses radiation exchanges and heat transfer which require various parameters as albedo, cloud temperature, cloud covers, dew point temperature and wind (Anderson, 1976). While, the degree-day approach which uses the temperature, degree day factor and lapse rate (6.49 °C/1000 m on average worldwide) can be used easily.

Gilgit is a scarcely gauged catchment with the only meteorological observatory situated at the elevation of 1460m, a watershed which has a mean elevation of 4058m which makes simulation using observed data particularly hard. Hence, accurate formulation of hydrological models in scarcely gauged cryosphere catchments using remotely sensed meteorological data is essential for assessment of streamflows for Pakistan. However, most rainfall-runoff models are not efficient in predicting daily streamflows because of the mixed contribution of snowmelt and rainfall sources (Martinec et al. 2007)

Previous studies have compared efficiencies of different types of models in simulating stream-flows of snow-fed areas. A comparison between Large Basin Runoff Model (LBRM) and Hydrologic Engineering Center-Hydrological Modeling System (HEC-HMS) indicated both LBRM and HEC-HMS models had difficulty reproducing peaks in early spring and late winter runoff, though HEC-HMS showed greater accuracies than LBRM (Gyawali and Watkins 2012; Yilmaz et al. 2011). Tahir et al. (2011b) integrated the MODIS snow cover product with the precipitation data in SRM and reported efficient simulations of daily streamflow for investigating the effect of climate change on the Hunza River, Pakistan.

Most previous studies on climate change show potential sensitivity to variations in climate change parametrization (Panday et al. 2014; Pokhrel et al. 2013). Climate changes show change in hydrological cycle and has received attention from hydrologists in context of both observations and projections (Akhtar et al. 2008; Immerzeel et al. 2009; Liu et al. 2013; Tahir et al. 2011b). However, most studies that have compared the direct impacts of climate change have not evaluated an efficient hydrological model for the specific catchment where there two major runoff sources are rainfall-runoff and snowmelt-runoff.

In this study we have applied SWAT (Soil and Water Assessment Tool) and HBV (Hydrologiska Byråns Vattenbalansavdelning model) to simulate stream-flows by integrating remotely sensed metrological data of ERA-Interim. We chose a snow- and glacier fed scarcely gauged, catchment of high altitude, Gilgit River basin in Pakistan to assess the two hydrological models with the available Remotely Sensed data types. After calibrating and validating the models we used them to assess the variation of streamflow and water availability under different climate change scenarios.

## 1.2 Study Area

The Hindu Kush, Karakorum and Himalayan (HKH) mountain ranges contain some of the largest glaciers; extensive perennial snow and ice covered areas of the world outside the Polar Regions and nourishes large Asian river basins with significant amounts of snow and glacier melt. The Gilgit River network comprises of the Ishkuman, Ghizar, Yasin, Hunza River and meet the Indus River near the village named Jaglot. The reaches allocated above of the basin are mostly covered with glaciers and with permanent snow. The Gilgit river basin boundary (Figure 1) is visualized by the location of the stream gauge installed by WAPDA at Gilgit City, Gilgit. Geographically the basin extends from 35.80°N, 72.53°E to 36.91°N, 74.70°E, a sub-catchment of upper Indus basin in the high Karakorum region. The total area of this basin is 12,659 km$^2$ and the variation of elevation in this area is from 1400 m to 7000 m with an average of 4258 m.

The only metrological station in this area is located in Gilgit city and is at an elevation of 1460 m which is one of the biggest drawbacks to using its data in such studies. The average annual precipitation is 591 mm according to the duration of this study (1990 – 2007), while, 60% of the streamflow discharge is a direct result of snowmelt in this area. Also, 80% of the total annual discharge is contributed during the summer season (April –August).

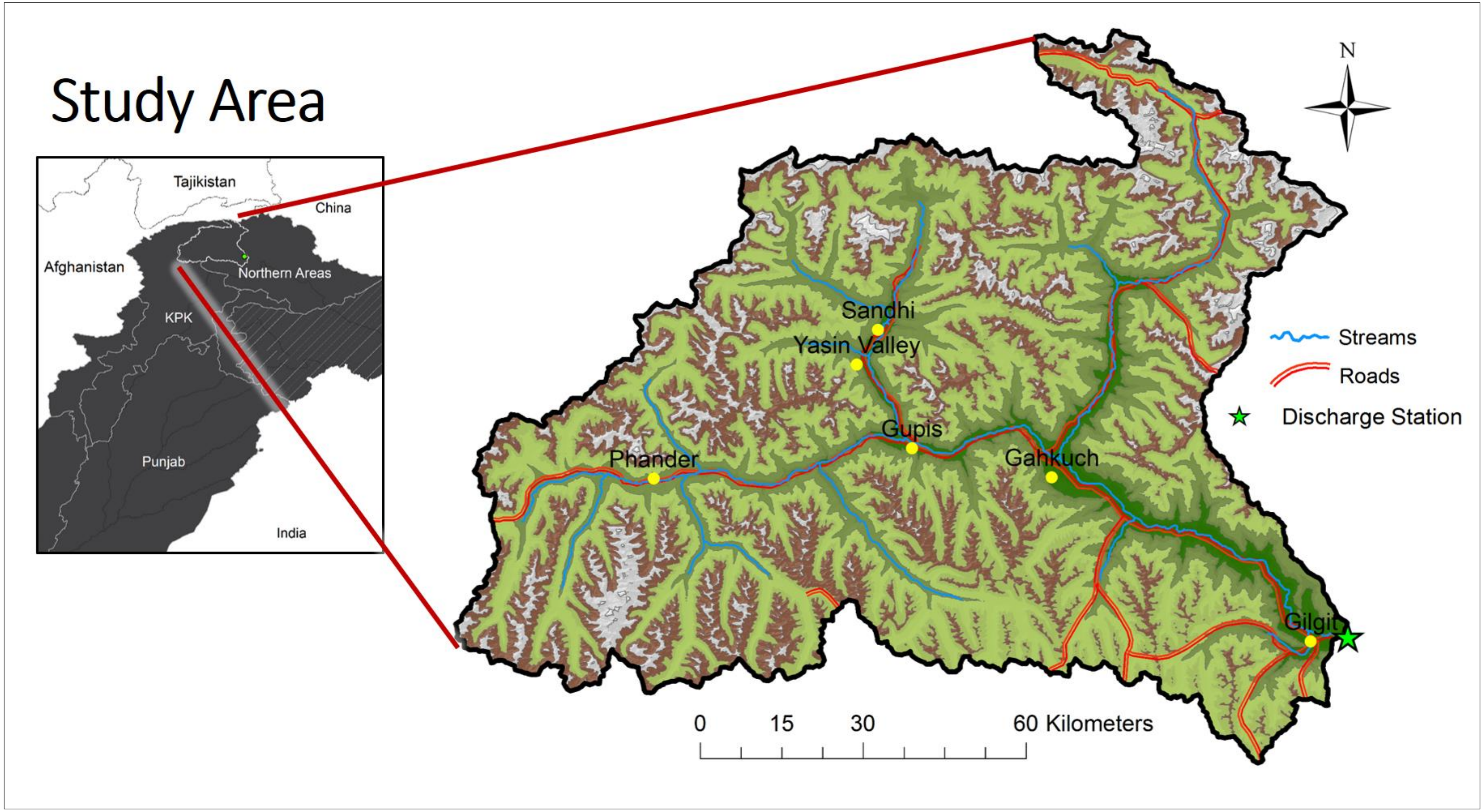

Figure 1. The study area of Gilgit River Catchment, the green star shows the WAPDA discharge station located just at the end of catchment

# CHAPTER 2

## DATA SETS

## 2.1 Satellite Data

### 2.1.1 Topographic Data

We used the Advanced Space Borne Thermal Emission & Reelection Radiometer (ASTER), Global Digital Elevation Model (GDEM) for the watershed delineation. For SWAT hydrological model the DEM was used to extract outlet points, river network points, area, slope and reach length. On the other hand, DEM was used to extract the elevation zones and area (Figure 2). The elevation of the area is greater than 1439 meter and its mean elevation is 4058 meters. Approximately 47.3% of the region lies in the elevation zone of 3500 – 4500 meters while 94% of it is above the height of 2000 meters.

### 2.1.2 Weather Data

Daily datasets of temperature, precipitation and evapotranspiration were taken from European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim. ERA-Interim is a computerized weather data from the ECMWF created by homogenized observation data (all kinds of non-climate changes in the data are detected by comparing nearby stations, their year-to-year variability). ERA-Interim data is mainly used for research purposes, and provides gridded data up to a period of 3-hours.

The main reason for not using the previously installed metrological weather station in the region is because of its location; not only it is located towards the side of the basin (installed in Gilgit city) but it is also at the very base of the valley with approximately 98% of the area at a higher altitude than the station. The station also provides monthly data values which can’t be used in HBV which requires daily weather data values.

## 2.2 Hydrometeorological Data

### 2.2.1 Discharge Data

We obtained the streamflow data at the Gilgit River station located in Gilgit city during 1990 – 2007 from the Surface Water Hydrology Project of the Water and Power Development Authority (WAPDA), as shown in Figure 1.

### 2.2.2 Weather Data

For SWAT hydrological model further data of wind speed, solar radiation and relative humidity was needed to simulate the streamflows. These datasets were acquired from PCMDI's Coupled Model Inter-comparison Project (CMIP3). In this project climate data simulated by some of the leading climate change centers from around the world are stored in one place for easy accessibility. The data is constructed by collecting modeled outputs of past, present and future climate simulations. The CMIP3 has more datasets than ERA-Interim but the ERA data is more accurate so only the datasets not available from ERA was acquired by CMIP3.

# CHAPTER 3

# MODEL APPLICATION

We have done the streamflow simulation on a daily basis for both SWAT and HBV in the Gilgit River basin. Similarly, we have calibrated the models for thirteen years (January 1990 to December 2003) and set the validation period for five hydrological years (January 2003 to December 2007). The quality of the simulated streamflows was produced using two different established descriptors: the percentage difference in volume (Dv%) and the Nash-Sutcliffe Coefficient (NSE) during the snowmelt period (April to August) and annually (January to December).

## 3.1 Application of HBV

The HBV model was inspired by the introduction of Nash & Sutcliffe (1970) which plead for a more realistic and less complex model as over parameterization was a big issue in hydrological models, even those with good $R^2$ performance. A model was required, that was realistic but had a few parameters and used the metrological datasets that can be easily acquired by the standard climatological and hydrological stations. The biggest benefit of this model could be derived for regions known as scarcely gauged catchments or catchments that had one or two gauging stations for a bigger area. So HBV model was directly conceptualized on these ideas back in 1972 (Bergström & Forsman, 1973). The basic criteria were:

(a) The model should base on a realism but it should not be too complex
(b) The number of free model parameters (parameter that cannot be predicted precisely) should be kept to a minimum.
(c) The model should not have a higher data demand than that of a standard climatological station for accurate results.
(d) Model usability should be high.
(e) Model shouldn’t have a high learning curve.

The very first effective run with the HBV hydrological model was carried out in the catchment of Lilla Tivsjön, Sweden the same year. (Figure 2, Bergström & Forsman, 1973). A snow routine was just introduced to the model just two years later

(Bergström, 1975). The model was lumped in the beginning but first steps towards distribution were taken by adding the area-elevation zoning in the same year as the snow routine. Over the next period of three decades (30 years) it was slowly improved without dramatically changing the initial basic structure of the model. The recent HBV model is best characterized as a semi-distributed conceptual model (Lindström et al., 1997). It consists of three main components:

(a) subroutines for snow accumulation and melt
(b) subroutines for soil moisture accounting
(c) response and river routing subroutines

The HBV model uses user-defined sub-catchments combined with elevation distribution on area and a rough classification of land use to form hydrological units. The numbers of parameters to calibrate for each routine are as follows:

(A) Snow routine has 4 parameters; Threshold Temperature (TT), Degree day Factor (CFMAX), Snowfall correction factor and a Water Holding Capacity of snow and ice (glacier). TT and CFMAX are the most important parameters not only for the routine but for the whole model.
(B) Soil moisture routine has 3 parameters; Maximum Soil Moisture Storage, Soil Moisture Value above which the potential evaporation from the soil will reach the actual evaporation and the relative contribution of runoff due to rainfall or snowmelt.
(C) Response and River routing has 4 parameters which determine how different zones above and below the surface will behave to runoff (above surface) or underwater flow (below the surface).

The HBV requires a smaller amount of input variables as compared to most of the other hydrological models. It normally uses 24-hourly values but can also take values recorded at smaller intervals, but it will not take values that are taken at much higher intervals at the 24 hours. The major datasets that are mandatory are the daily precipitation, air temperature and some calculations of potential evapotranspiration (can be daily or estimation of monthly resolution which is an exception to 24-hour rule as the model can modify these values for each day based on the daily temperature). For more accurate results, the elevation, land use and land cover, soil classifications and glacier coverage by area of each sub-catchments can be added too.

The model is highly accurate for many scales, from only small research catchments of less than a kilometer squared to continental catchments of the scale representing of the whole land area of 1,729,000 km$^2$ draining into the Baltic Sea (Graham, 2004).

HBV, the first choice simulations tool for Sweden, Norway and Finland- the catchments that it was initially designed for- now has been gaining popularly since its conceptualization. It is also used in a large number of countries outside the Nordic region too; more than 50 countries all over the world and the list is growing. Since the last decade of the 20th century with the growing concerns of global warming and climate change, HBV has also been extensively used for climate change stimulation to study their impacts on water resources in these countries (Vehviläinen & Lohvansuu, 1991; Saelthun et al., 1998; Bergström et al., 2001).

### 3.1.1 Ungauged basins

Evaluation in ungauged catchment is the sole goal of most hydrological modelers but it has since long been pointed that a simplistic conceptual model like HBV would have lesser potential, because of difficulties in the pointing of its

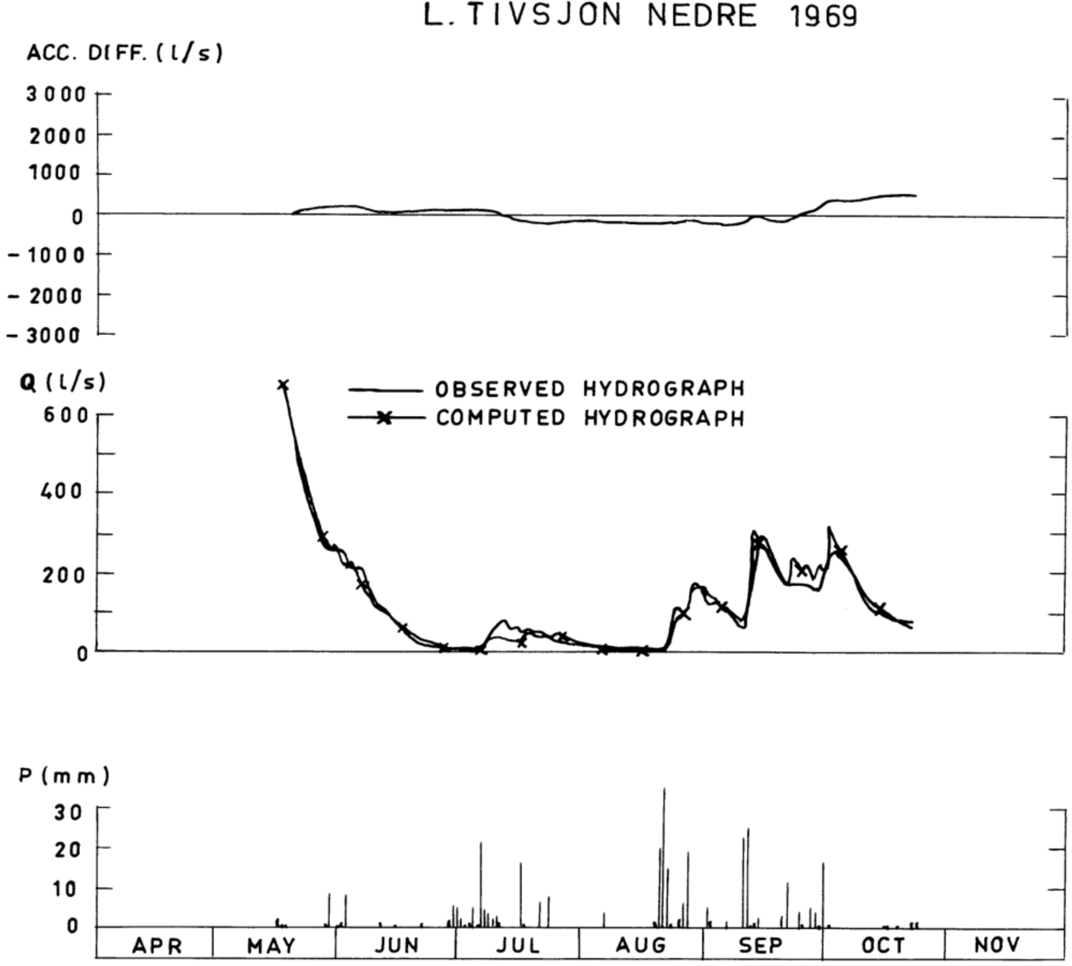

Figure 2: The very first successful run by HBV model in 1972. The catchment is the Lilla Tivsjön research basin in northern Sweden, with an area of 13 km$^2$

parameters. The progress towards calculating in ungauged catchments was mainly driven by the environmentalists, which required discharge input to find the movement of nutrients based on calculating their concentrations.

There were generally three possible methods of finding discharge flows in streams/rivers without any dataset. First of them was to utilize data from neighboring streams through statistical strategies. The second was to go through such a great amount of involvement with an applied model that we can outline ideal estimations of its factors, or relate them to basin attributes. Thirdly, to use a model that is so practically precise that it needn't bother with calibration by any means. The first case had been in use for quite a long time while the second one is used as supplement to the first method (statistical methods). It was, nonetheless, not thought practical to introduce the physically correct modelling option, due to the non-availability of proper and precise input data.

## 3.2 Application of SWAT

SWAT is a persistent or continuous, physically based, semi-distributed hydrologic model initially made by the US Department of Agriculture (USDA) and the Texas Experimental Station (TES) in the mid-1990s. SWAT is a watershed, scale model created to foresee the effect of Land administration practices on water, sediments, and rural substance yields in extensive, complex watersheds with shifting soils, land use, and administration conditions over drawn out stretches of time. The Model is based on readily available inputs and outputs and empowers users to study long term impacts.

SWAT has been used particularly for simulation of single or several number of watersheds which are connected hydrologically. The watershed is separated into 2 components, the land phase and routing phase. Firstly, for land phase, river basin is divided into sub basins, and each of these is composed of numerous hydrological response units (HRUs), based on the land use and soil distributions. Secondly, a meteorological component contains models to incorporate snowmelt, evapotranspiration, and precipitation data. (Neitsch et al. 2002, 2005).

In SWAT, the modified SCS-CN method is widely used for calculation of Surface Runoff generation. CN changes when land use changes accordingly which leads to the estimation of runoff. The execution of SWAT is frequently judged by a straightforward split-example test utilizing authentic release arrangement and area use designs. The inferred parameter qualities are then thought to be indistinguishable for the new land use situations aside from CN, which will change with new land use situations. In any case, land use change can modify direct runoff, as well as evapotranspiration, speeds of overland stream and channel stream etc. In this way, alternate parameters connected with these procedures ought to likewise be changed with new land use scenarios.

## 3.3 Climate Change Scenarios

We discussed future climate change cases in comparative river/stream-flow simulations with two models, pondering the critical temperature effect “t” and precipitation “p”. For the climate variation detection, we used January 2002 to December 2007 as a baseline time period (current scenario).

- Scenarios 1: An increment of 2°C – 4°C in baseline time temperature and keeping precipitation at its original or actual value. A temperature increment in this area of maximum 3.7°C by the end of this 21st century has been predicted by IPCC (2007). A possible decrement of 2°C in temperature was also used to calculate how it impacts stream discharge.
- Scenarios 2: We considered an increase of 10% – 20% change in precipitation based on quite possible future changes in precipitation. It generated a more than 20% increase in average yearly precipitation in the region of Himalayan. A possible decrement of 10% in precipitation was also checked to visualize its effect on value of discharge.
- Scenarios 3: We made 4 different scenarios of precipitation “P” and temp “T” due the reasons discussed above (IPCC 2007, 2014). And for this scenario, we have considered:

  a) an increase in present (baseline) precipitation by 10% and temperature by value of 2°C

  b) a decrease in present precipitation by value by 10% and increase in temperature by value of 2°C

  c) an increase in present precipitation by value of 10% and a decrease in temperature by value of 2°C

  d) a decrease in present precipitation by value of 10% and in temperature by value of 2°C

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 HBV Model

Sensitive parameters were evaluated by using “trial and error method” and the “Monte Carlo simulations”. HBV is particularly sensitive to Degree day factor (CFMAX) by changing it in the range (Table 1) the efficiency of the model increases to approximately 20% and the difference in Volume of Discharge decreases by 50%. Other factors that showed sensitivity were “Maximal flow from upper to lower GW-box” (PERC) and the routing, “length of weighting function” (MAXBAS) but it was very small with an efficiency increase of 3% and a Volume of Discharge decreases of 4%.

### 4.1.1 Efficiency with Elevation

Elevation zones of equal vertical extent 1, 3, 5 and 7 were applied to perform the standard version of model. The territory of every elevation was resolved from a computerized “Digital Elevation model” (DEM). To perform the model calculations mean elevation inside an elevation zone was utilized. Parameter contents were not permitted to fluctuate for the diverse elevation zones. For each and every elevation zone, the temperature and the precipitation values are generated by the model from the calculated data according to Height Increment Variables of PCALT [%/100 m] and TCALT [ºC / 100 m] are used that define how precipitation and temperature values should be corrected with elevation.

The increase in the number of elevation zones from one to three and then to five showed a great increase in the efficiency while further increasing the elevation zones make no further impacts (Figure 3)

| Parameter | Explanation | Unit | Minimum | Maximum | Used |
|---|---|---|---|---|---|
| **Snow Routine** | | | | | |
| *TT* | Threshold temperature | °C | -1 | 1 | 0.88 |
| *CFMAX* | Degree-day factor | mm $°C^{-1}$ $d^{-1}$ | 0.5 | 4 | 2.3 |
| *SFCF* | Snowfall correction factor | - | 0.9 | 1.1 | 1.1 |
| *CWH* | Water holding capacity | - | 0 | 0 | 0 |
| *CFR* | Refreezing coefficient | - | 0 | 0 | 0 |
| **Soil and evaporation routine** | | | | | |
| *FC* | Maximum Snow Melt | mm | 100 | 500 | 400 |
| *LP* | SM threshold for reduction of evaporation | - | 0.3 | 1 | 1 |
| *BETA* | Shape coefficient | - | 1 | 6 | 6 |
| **Groundwater and Response routine** | | | | | |
| $K_0$ | Recession coefficient | $d^{-1}$ | 0.1 | 0.5 | 0.1 |
| $K_1$ | Recession coefficient | $d^{-1}$ | 0.01 | 0.2 | 0.05 |
| $K_2$ | Recession coefficient | $d^{-1}$ | 0.005 | 0.1 | 0.01 |
| *UZL* | Threshold for $K_0$-outflow | mm | 0 | 70 | 20 |
| *PERC* | Maximal flow from upper to lower GW-box | mm $d^{-1}$ | 0 | 4 | 1 |
| **Routing routine** | | | | | |
| *MAXBAS* | Routing, length of weighting function | d | 1 | 2.5 | 1.45 |

Table 1 Parameters and their ranges, and the final value used in the model

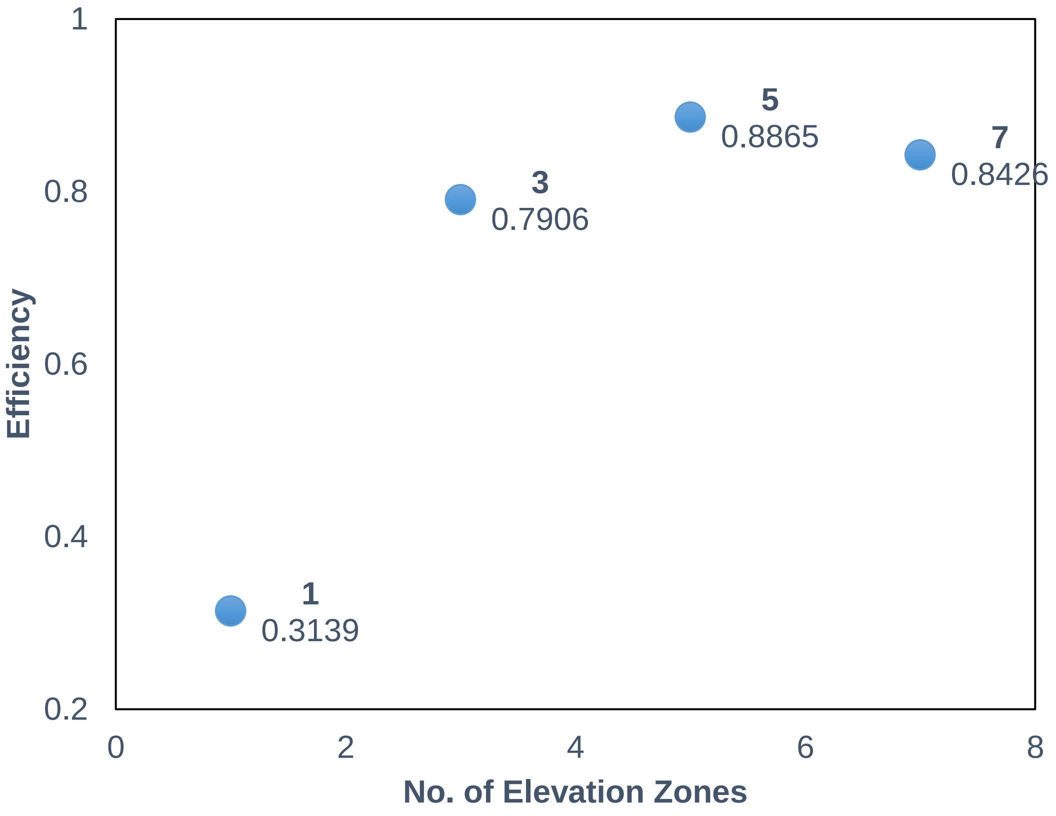

Figure 3: Model Goodness versus the number of elevation zones

### 4.1.2 Calibration and Validation

Both models were calibrated based on the results obtained from the sensitivity analysis and input weather data from ERA daily data sets of temperature, precipitation and evapotranspiration. The Nash and Sutcliffe coefficient (NSC) of efficiency, along with the coefficient of determination ($R^2$) and the difference in Volume (Dv%) were used for the model evaluation. The NSC obtained was 0.93 while the $R^2$ value was also 0.93, there was almost no difference in volume of discharge in the observed and simulated values as Dv% was less than even 1% (0.23) (Table 2) (Figure 4).

Similarly, the results of the Validation period were also exceptional as the NSC obtained was 0.75 while the $R^2$ value was 0.88, the Dv% was 26.3% (Table 2) (Figure 5).

## 4.2 SWAT Model

In the first step, the sensitivity analysis was performed. Sensitive parameters were identified using SWAT-CUP (calibration and uncertainty procedures) and their values were adjusted according to the local study area properties. (Table 2). SCS curve number was the most sensitive parameter and by increasing its value the surface runoff is also increased. Its value was adjusted to 77 from initial value of 83. Second parameter was hydraulic conductivity of soil. It depends on the soil type and its percentage in a specific sub-basin. Sand has the highest conductivity whereas clay is least permeable. By increasing the CNCOEF (CN coefficient) the evapotranspiration decrease, eventually resulting in decreased base flow and tile flow but increased surface runoff. CN_FROZ is the curve number when soil temperature is at 0 C; by increasing its value, discharge is increased in wet soil but decrease in dry frozen as water percolates through dry soil. Slope is also important as higher slope will have higher subsurface flow due to large hydraulic gradient.

### 4.1.1 Calibration and Validation

In the next step, the model was calibrated based on the results obtained from the sensitivity analysis and observed values from the monitoring stations. The Nash and Sutcliffe coefficient (NSC) of efficiency, along with the coefficient of determination ($R^2$) and the difference in Volume (Dv%) were used for the model precision.

The NSC obtained was 0.60 while the $R^2$ value was 0.70, the difference in volume (Dv%) of discharge in the observed and simulated values was 34% (Table 2) (Figure 6). Similarly, the NS value for validation period was found 0.74, while, the $R^2$ and Dv% value was 0.79 and 10,6%, respectively (Table 2).

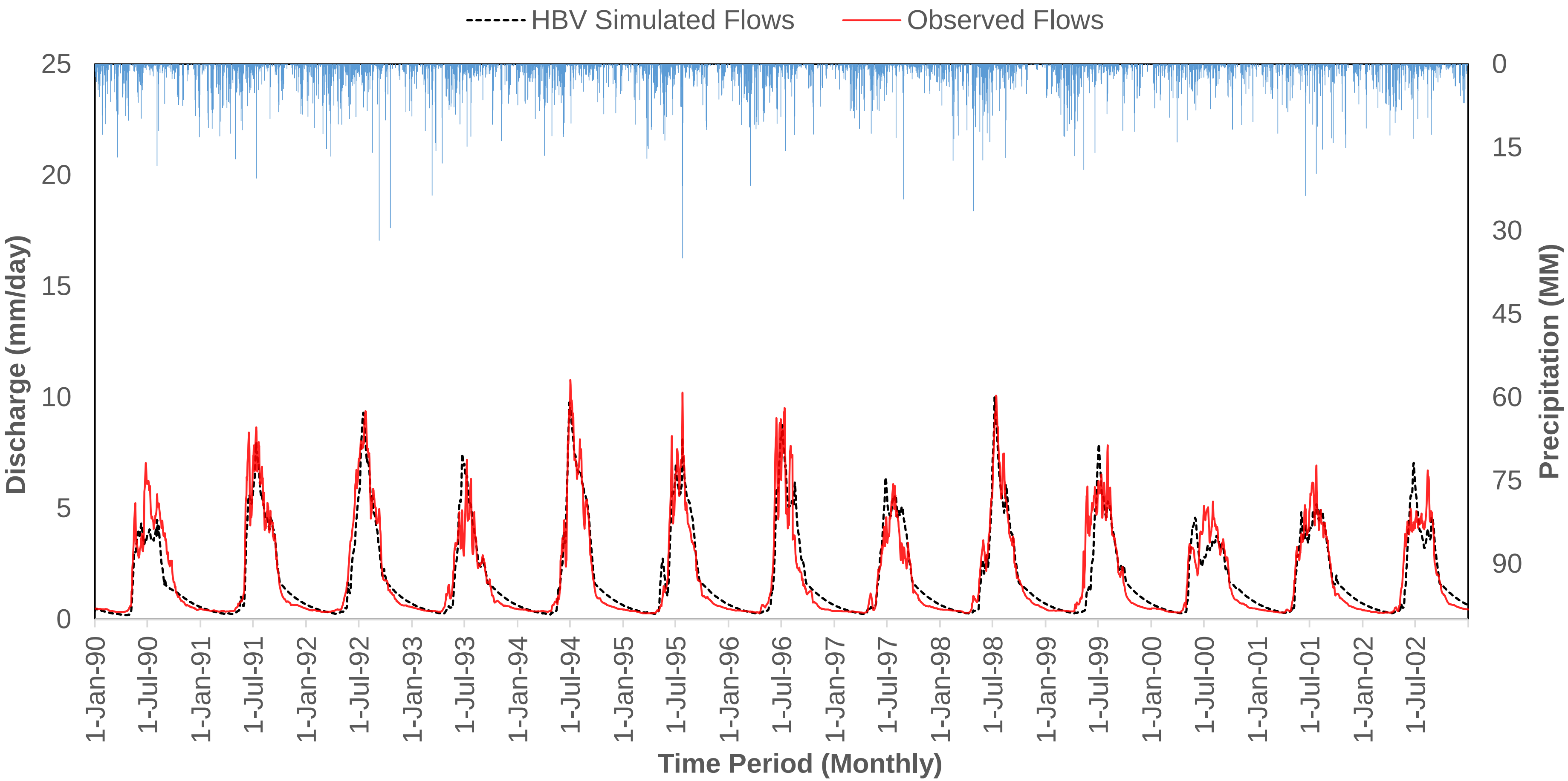

Figure 4 Time Series analysis of HBV simulated streamflow for calibrated period (1990 – 2002)

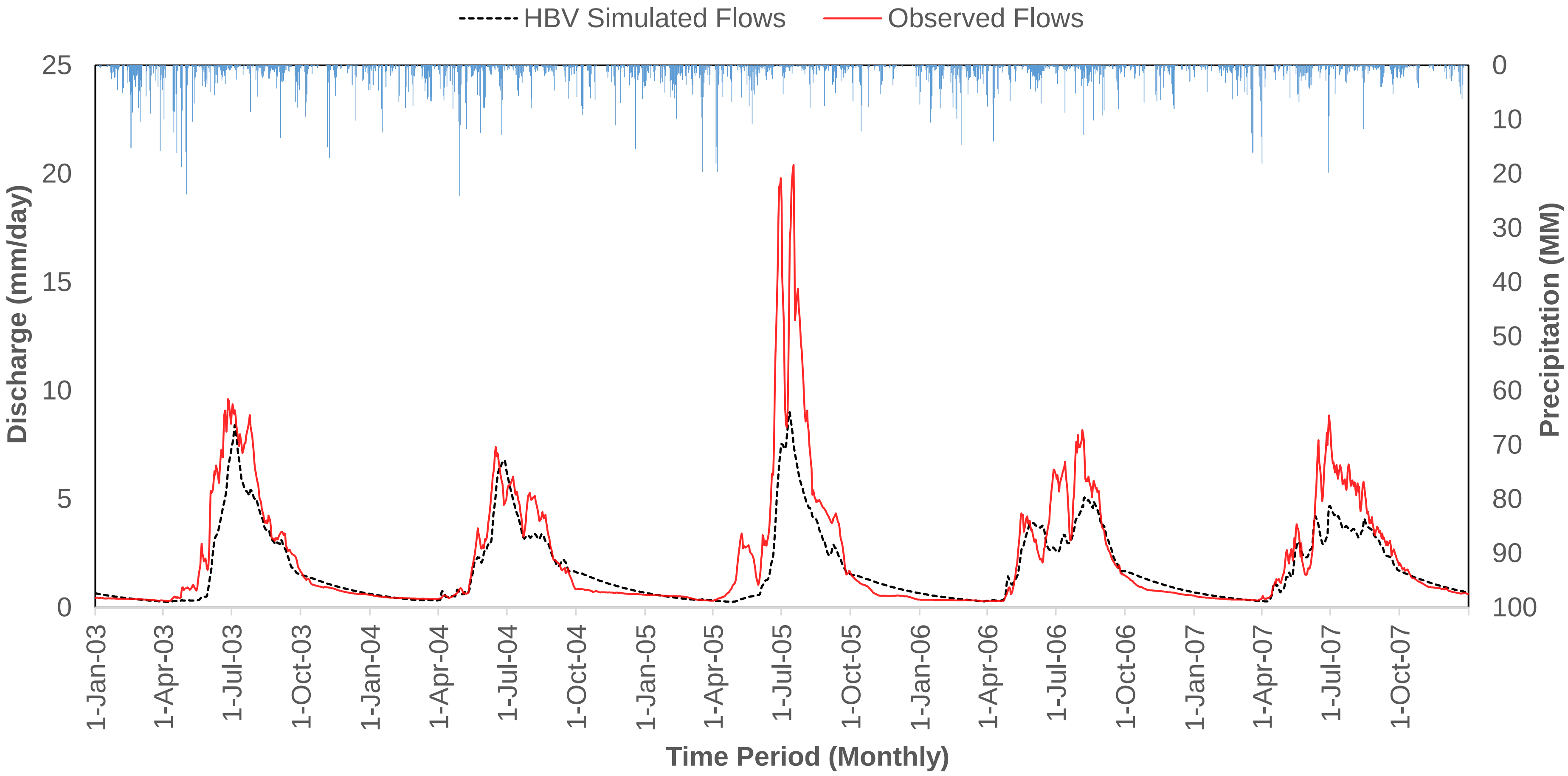

Figure 5 Time Series analysis of HBV simulated streamflow for validation period (2003 – 2007)

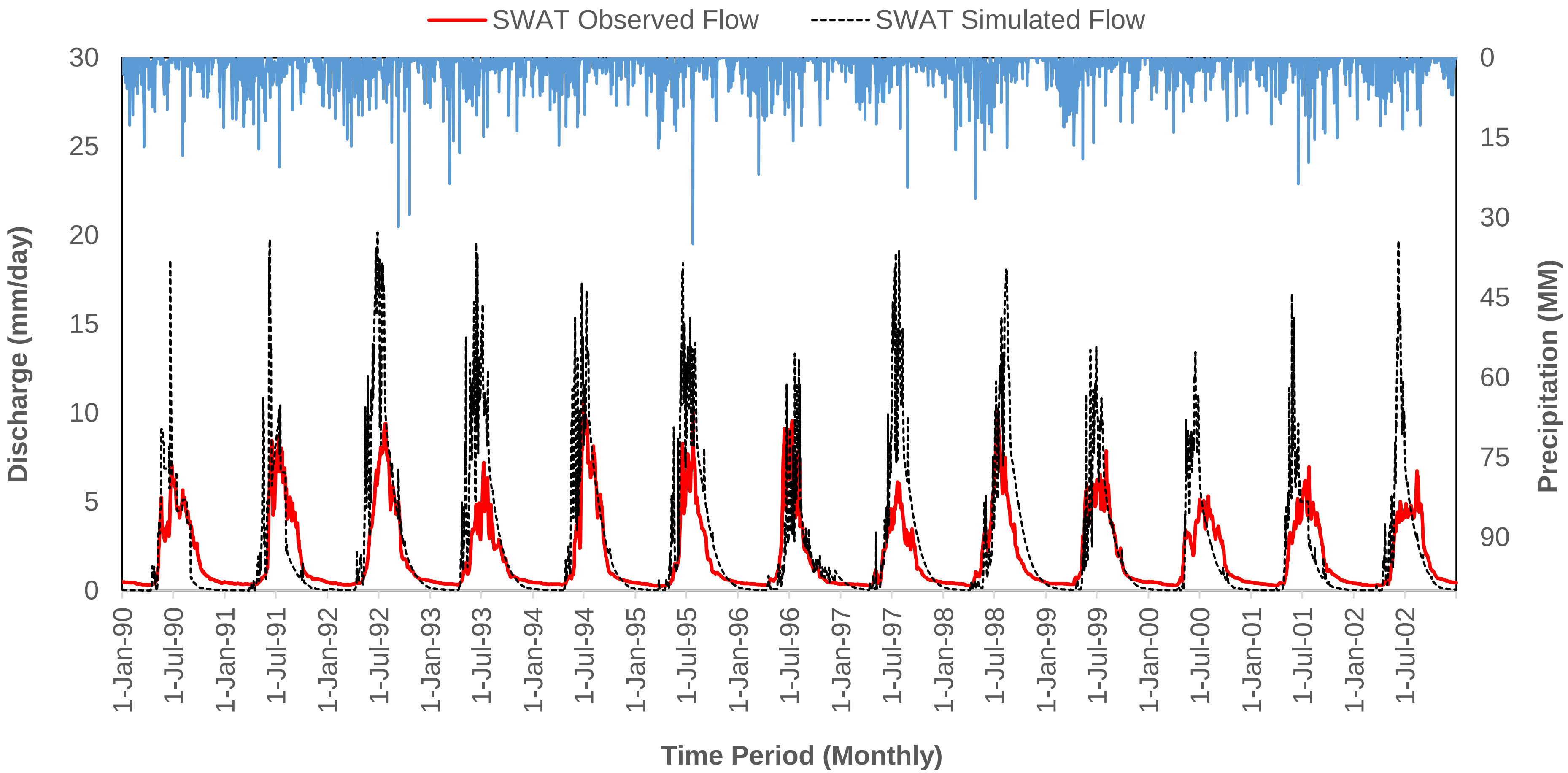

Figure 6 Time Series analysis of SWAT simulated streamflow for calibrated period (1990 – 2002)

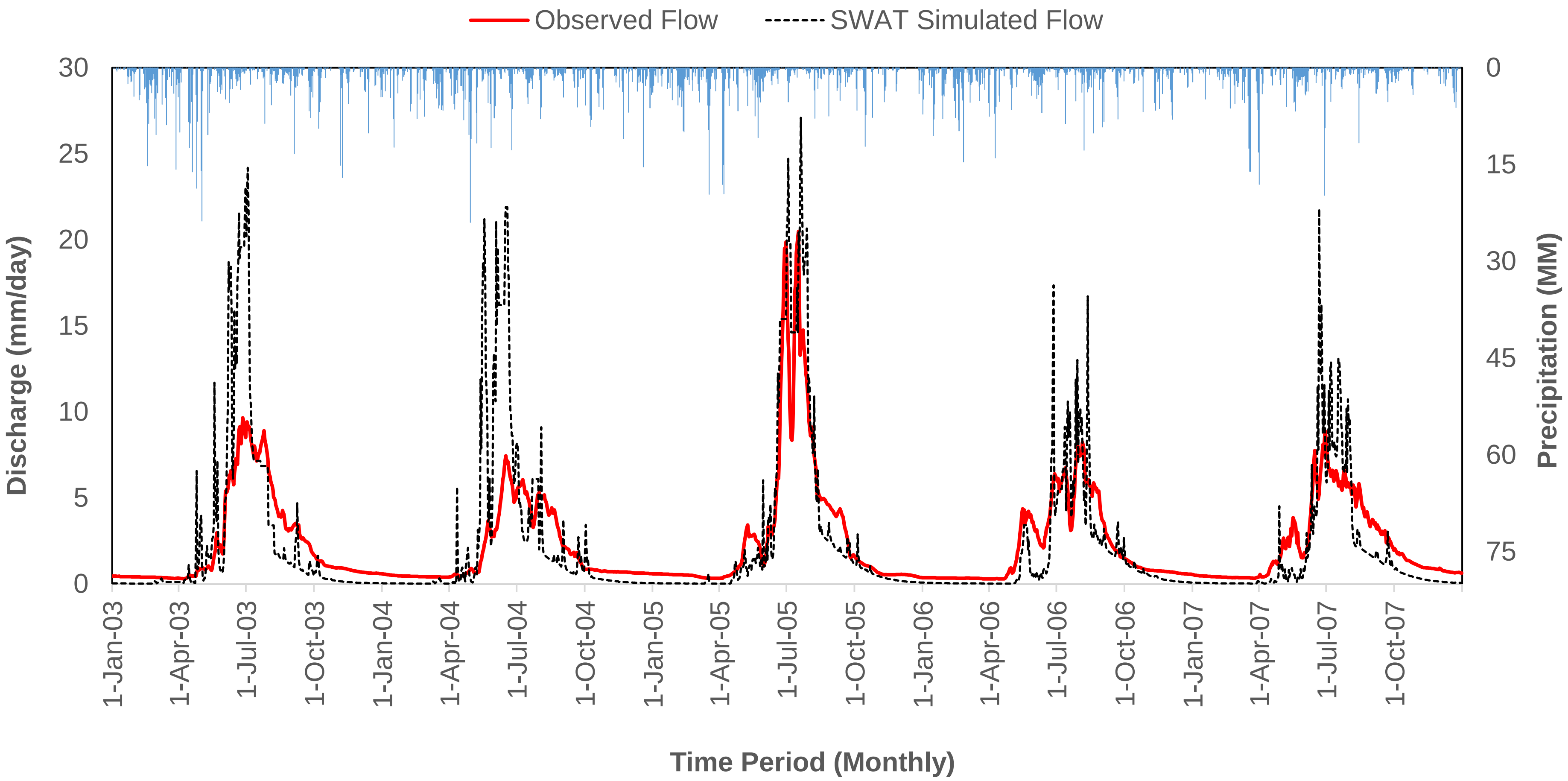

Figure 7 Time Series analysis of SWAT simulated streamflow for calibrated period (1990 – 2002)

Table 2: Statistical comparison between simulated and observed stream-flow by HBV and SWAT for the calibration and validation periods during snow-melt season and for full hydrological year

| **Hydrological Years** | | **Calibration (1990 - 2002)** | | **Validation (2003 - 2007)** | |
|---|---|---|---|---|---|
| **Yearly** *(January - December)* | | **HBV** | **SWAT** | **HBV** | **SWAT** |
| Coefficient of Determination | **$R^2$** | 93 | 71 | 88 | 80 |
| Nash-Sutcliffe Coefficient | **NSE** | 93 | 60 | 76 | 75 |
| Difference in Volume | **Dv (%)** | 0.23 | 34 | 26 | 11 |
| **Summer Period** *(April - August)* | | | | | |
| Coefficient of Determination | **$R^2$** | 91 | 53 | 82 | 72 |
| Nash-Sutcliffe Coefficient | **NSE** | 89 | 35 | 58 | 45 |
| Difference in Volume | **Dv (%)** | 7 | 46 | 39 | 12 |

## 4.3 Climate Change Scenarios

We have applied climate change scenarios for both these models by varying Precipitation, Temperature and Precipitation-Temperature combined according to which these model predict trend shift and discharge outputs, with the help of these scenarios maximum future streamflow in Gilgit river basin can be analyzed. We considered time period from January 2002 to December 2008 as our baseline period or current scenario.

I. **Precipitation Variations:** For precipitation we evaluated three conditions by variating it from -10% to 20%.

   By **increasing the value of precipitation by 10% and 20%** the trend in discharge remain the same but there is an increase in discharge and peak values for both SWAT and HBV. The peaks for 20% increase in precipitation are higher as compared to the peaks of increase by 10% in precipitation.

   By **decreasing the value of precipitation by 10%** the discharge for HBV follows the same trend as the baseline discharge but there is a slight decrease in the overall volume for the whole year. For SWAT the only anomaly is the month of July where the peak rises above the baseline discharge but otherwise follows the same trend as HBV (Figure 8, Figure 9).

II. **Temperature Variations:** Again we evaluated 4 conditions for temperature by variating from -4°C to +4°C.

- *SWAT:* In the **first condition** when there is an **increase in temperature by 2°C**, there is increase of discharge. Similarly, with an increase of 4°C in temperature, results are quite disparate as with further addition of temperature it produces comparatively lesser discharge in months of June and July- otherwise a period of maximum discharge in the region. And in case of 2-4°C reduction in temperature, as compared to our current scenario discharge is maximum for the month of July. The trend actually shifts to late summer months of August and September (Figure 10).
- *HBV:* Due to High accuracy of HBV in high altitude regions it gives quite considerable results with its regime more shifted towards early summers. In case of this model with addition of 2°C in temperature greater discharge will be produced in months of April, May and June as compared to our Baseline

temperature discharge. With an increase of 4°C in temperature, it will give maximum discharge level opposite to SWAT model prediction. The peak is steeper with a 2°C reduction in temperature with a lesser discharge level (from our baseline conditions) but remains same in the month of July. Similarly, for a 4°C reduction in temperature, minimum discharges are observed as compared to all the above mentioned scenarios. There is a negligible shift in the trend (Figure 11).

III. **Temperature and Precipitation Variation** (Combined): We evaluated 4 conditions of the combined effect of temperature and precipitation by varying them from -2C-2C & from -10%-10% respectively.

- *SWAT*: In the **first condition** when there is an **increase in temperature by 2°C and in precipitation by 10%,** there is a maximum discharge of 186mm/day in the month of June after which it gradually drops and roughly equals the baseline conditions in the month of July but drops to minimum in the month of August i.e. 3mm/day as compared to baseline discharge which is 36mm/day.

  In the **second condition**, when there is **an increase in temperature by 2C and decrease in precipitation by 10%,** the discharge follows the same trend as the baseline conditions for the first half of the year but decreases significantly in the second half of the year.

  In the **third condition**, when there is **a decrease in temperature by 2C and increase in precipitation by 10%,** the trend is shifted to the late summer with a significantly high peak i.e.243mm/day in July as compared to our baseline condition with a discharge of 146mm/day for the same period of time.

  In the **fourth condition**, when there is **a decrease in temperature by 2C and in precipitation by 10%,** we see the same trend as in the third condition mentioned above with only the difference in amount i.e. 186mm/day for the month of July.

- *HBV*: In the **first condition** when there is an **increase in temperature by 2°C and in precipitation by 10%,** there is a shift in trend towards the early summer along with the increase in volume of discharge which is observed throughout the year. The peak of 113mm/day is in the month of July.

  In the **second condition**, when there is **an increase in temperature by 2C and decrease in precipitation by 10%,** there again is a shift towards early summer but slightly less than the one in first condition resulting in a higher discharge values for this period (early summer) but it falls below the baseline discharge as later in the summer after the month June.

In the **third condition**, when there is **a decrease in temperature by 2C and increase in precipitation by 10%,** there is no major shift in the trend but there is a significant increase in the quantity of discharge which peaks steeply in the month of July with a value of 112mm/day. However, for the rest of the year the volume of discharge is lower than our baseline condition.

In the **fourth condition**, when there is **a decrease in temperature by 2C and in precipitation by 10%,** we see the same trend as in the third condition mentioned above, with only the difference in amount of the discharge which remains significantly lower throughout the year as compared to our baseline with a value of 92mm/day for the month of July (Figure 13).

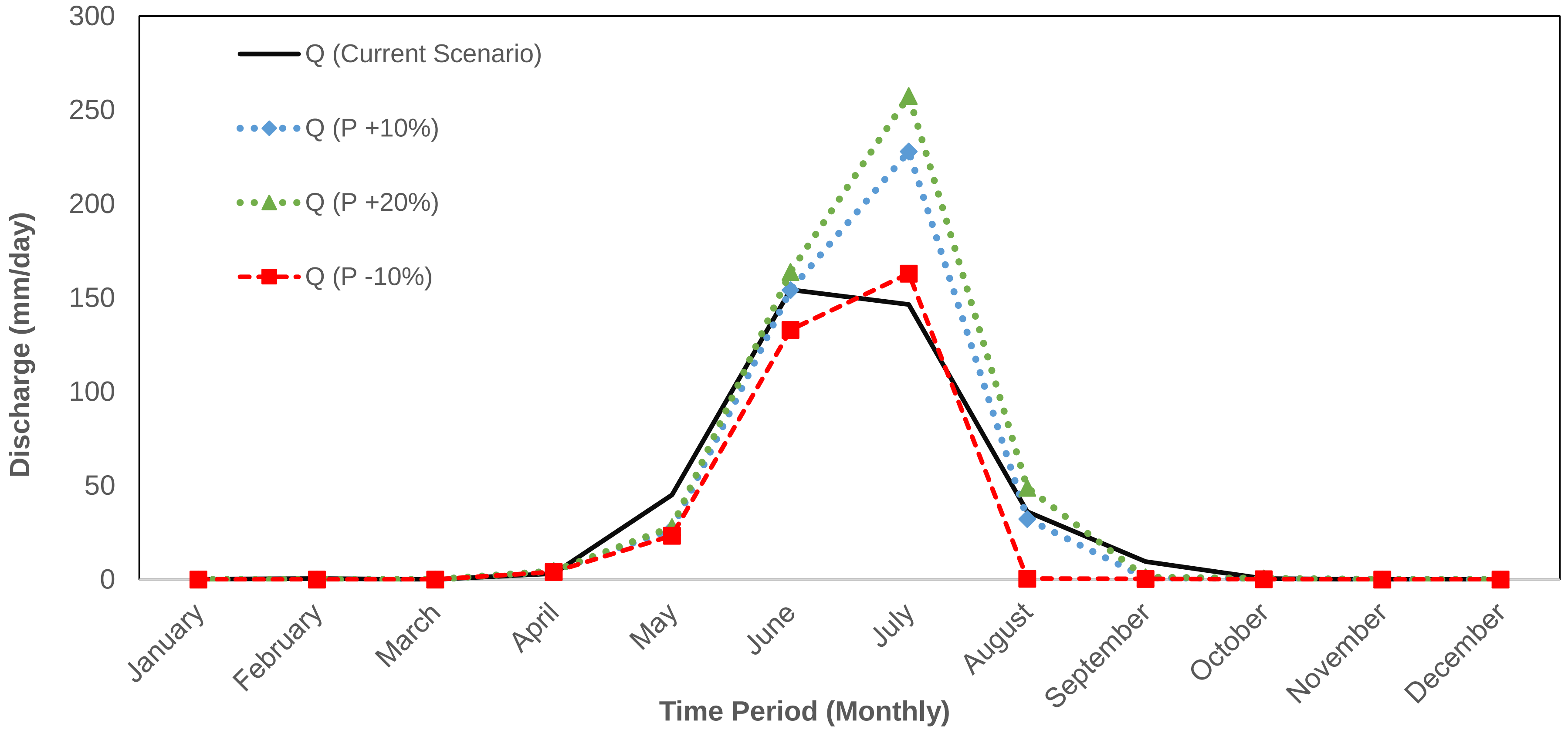

Figure 8 Streamflow Modeling of Monthly Time period using SWAT for baseline ($Q_{baseline}$) and potential future scenarios under precipitation change.

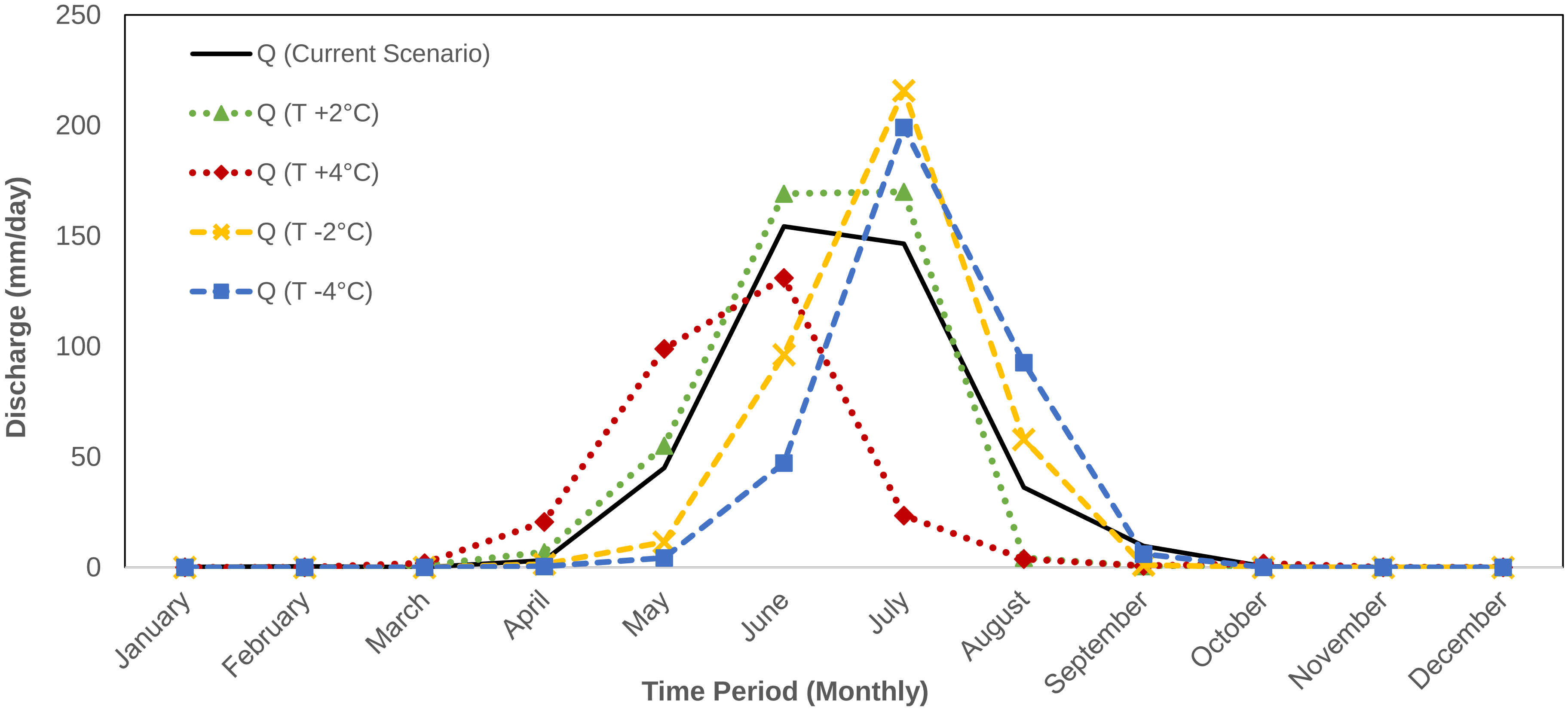

Figure 9 Streamflow Modeling of Monthly Time period using SWAT for baseline ($Q_{baseline}$) and potential future scenarios under temperature change.

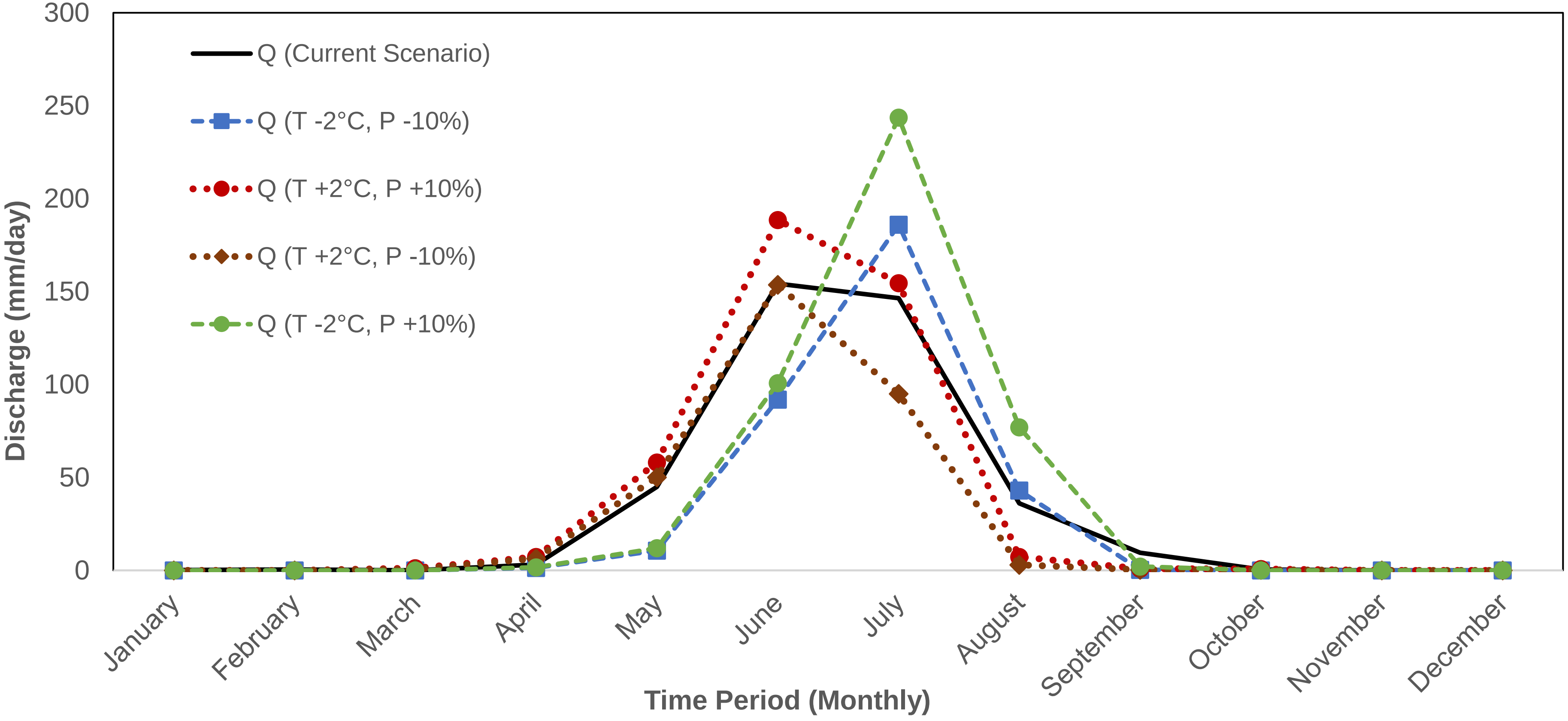

Figure 10 Streamflow Modeling of Monthly Time period using SWAT for baseline ($Q_{baseline}$) and potential future scenarios under temperature and precipitation change.

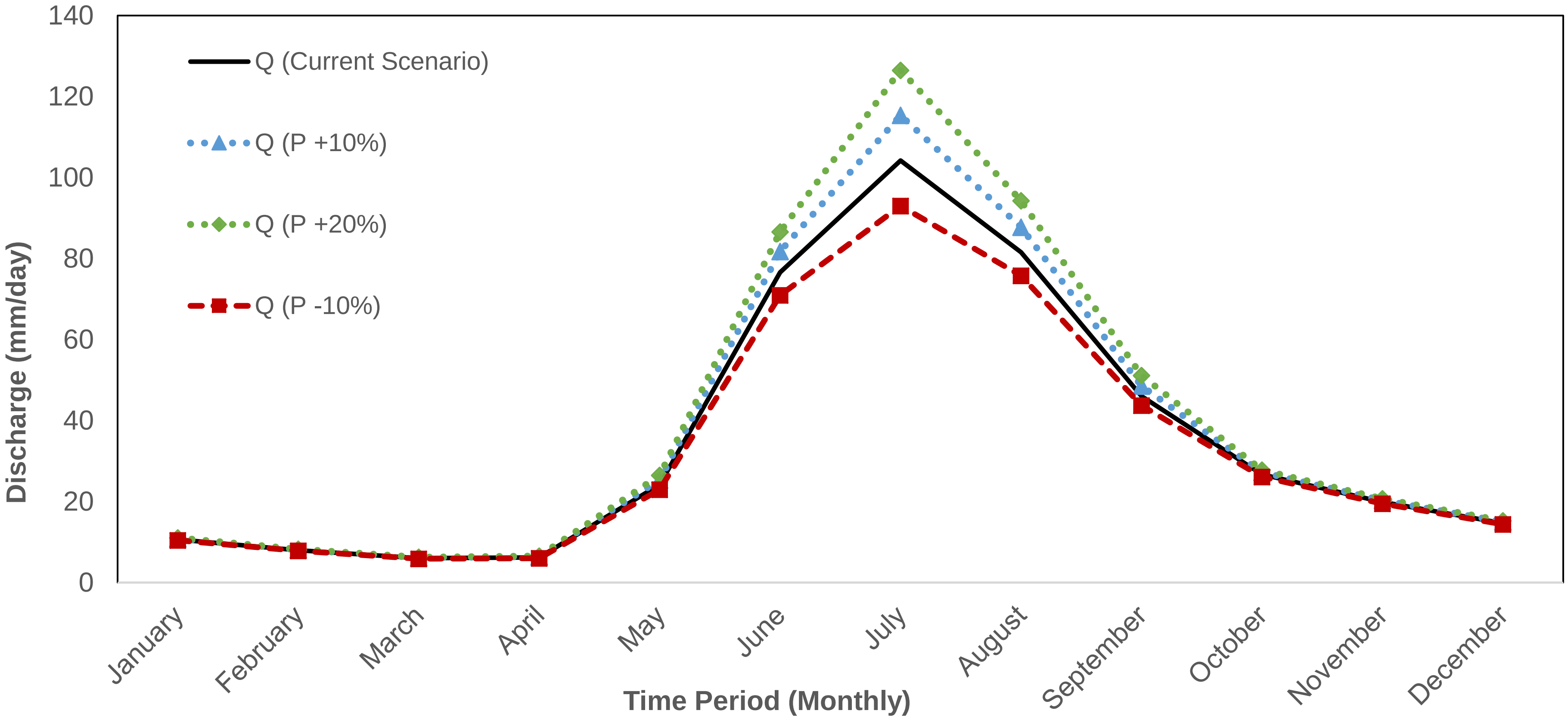

Figure 11 Streamflow Modeling of Monthly Time period using HBV for baseline ($Q_{baseline}$) and potential future scenarios under precipitation change.

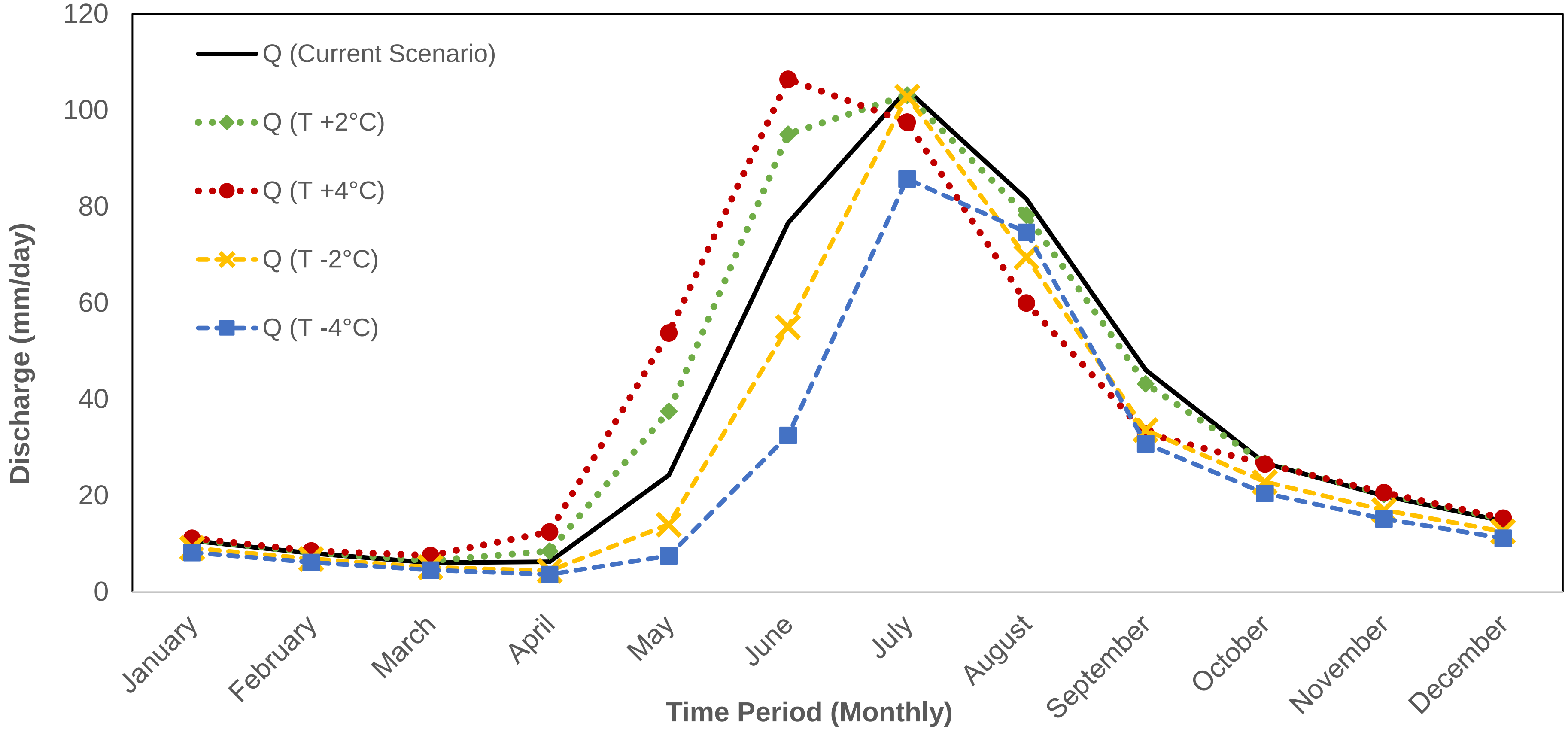

Figure 12 Streamflow Modeling of Monthly Time period using HBV for baseline ($Q_{baseline}$) and potential future scenarios under temperature change.

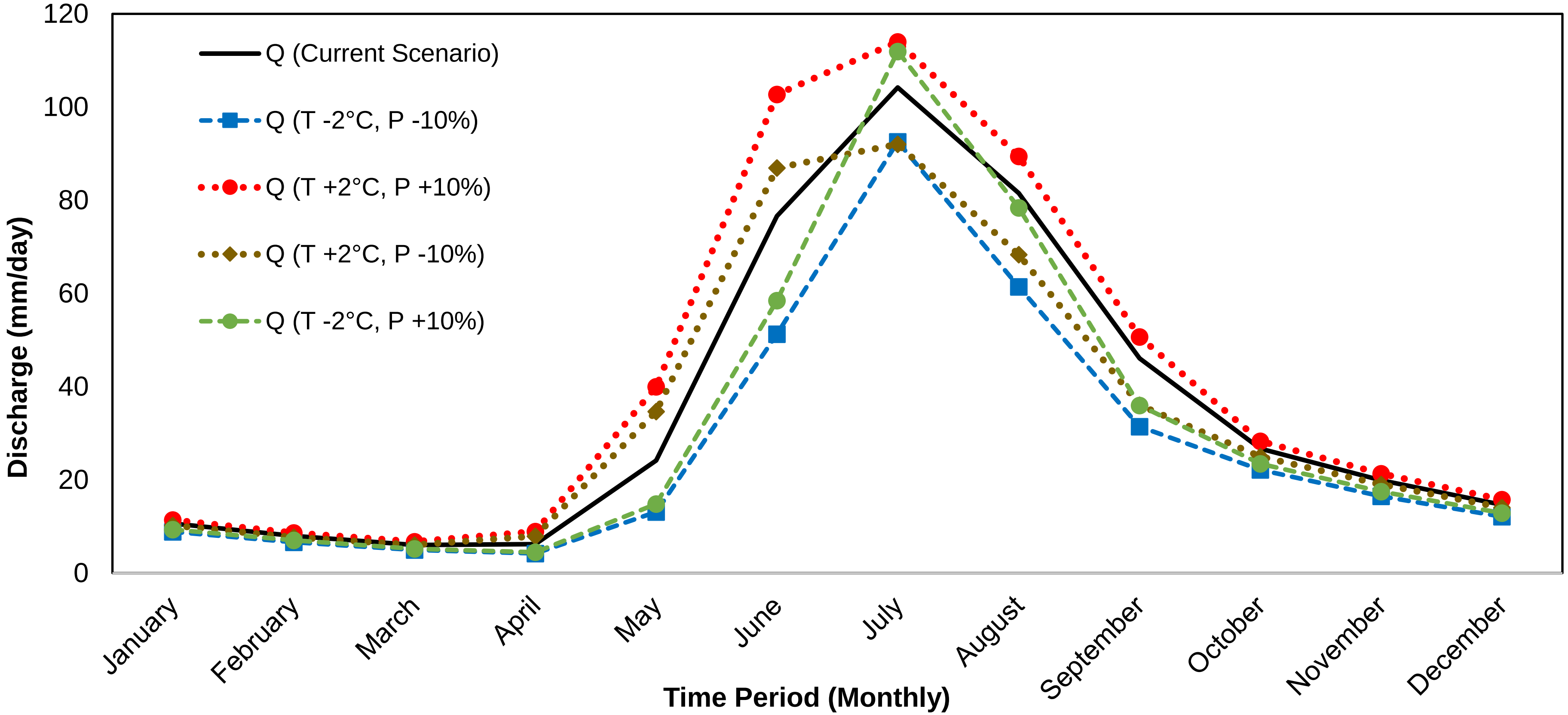

Figure 13 Streamflow Modeling of Monthly Time period using HBV for baseline ($Q_{baseline}$) and potential future scenarios under temperature and precipitation change.

Table 3 Percentage change in streamflow under future climate change scenarios simulated by HBV and SWAT

| **Potential scenarios** | **HBV** | | | **SWAT** | | |
|---|---|---|---|---|---|---|
| | Annual | Summer | Winter | Annual | Summer | Winter |
| T +2°C | 6.60 | 7.90 | 1.76 | 2.96 | 2.89 | 127.43 |
| T +4°C | 6.47 | 7.16 | 4.26 | -28.71 | -29.44 | 325.66 |
| T -2°C | -16.92 | -17.60 | -14.70 | -2.98 | -2.71 | 3.54 |
| T -4°C | -29.16 | -30.72 | -23.86 | -11.60 | -11.35 | 0.00 |
| P +10% | 6.65 | 7.79 | 2.05 | 12.95 | 13.15 | 45.13 |
| P +20% | 13.30 | 15.61 | 3.96 | 27.49 | 27.70 | 54.87 |
| P -10% | -6.65 | -7.76 | -2.16 | -18.13 | -17.95 | 18.23 |
| T -2°C; P -10% | -23.35 | -25.02 | -17.13 | 5.79 | 5.60 | 173.45 |
| T +2°C; P +10% | 17.20 | 19.79 | 7.28 | 10.54 | 10.84 | 5.31 |
| T +2°C; P -10% | -3.99 | -3.78 | -4.52 | -21.77 | -21.80 | 87.61 |
| T -2°C; P +10% | -10.50 | -10.22 | -12.25 | -15.74 | -15.51 | 2.65 |

# CHAPTER 5

## CONCLUSONS

The study is concerned with two major aspects of Gilgit river basin **a)** analysis of water resource availability by application of two hydrological rainfall-runoff models and **b)** climate change analysis and its impacts on the hydrological regime.

A. Application of Hydrological Models:

The investigation concluded that HBV a rainfall-runoff model can simulate daily streamflows highly efficiently in high-altitude ungauged basins of Gilgit river basin. Rainfall, temperature and evaporation are the only climate data need for accurate simulation of runoff. Therefore, ERA-Interim highly accurate weather datasets were used as the only metrological weather station in the Gilgit basin was poorly placed to perform any meaningful analysis of the area.

Additionally, the investigation concludes that the Soil and Water Assessment Tool (SWAT) is not very efficient in simulations as it was poor at capturing rapid snowmelt generated runoff peaks during summer season specifically in high-altitude part of the catchment. The model would not only randomly predict very high peaks some days (as shown in the figure 6 and 7) but also requires a higher data demand for any kind of meaningful predictions.

The performance of HBV is very high while SWAT is somewhat respectable, as shown by the Nash coefficient of HBV which was 93.39% and Difference in volume Dv% of 0.23% compared with values of SWAT which were 60.10 % and 34.26% respectively. HBV was more valuable in rare information situations since it utilized precipitation input information as a part of the type of both melted precipitation as well as strong snow spread, which supported it to overcome remotely detected precipitation or watched information procurement mistakes.

B. Climate change analysis:

For projection of runoff under different climate change scenarios, the 4th (2007) and 5th (2013) assessment reports of Intergovernmental Panel on Climate Change (IPCC) were used. In this part the HBV showed sensitivity to both temperature and precipitation changes, while SWAT showed a very high sensitivity to precipitation but almost none to temperature variations. Similarly, HBV showed the accurate hydrological trends for cryosphere catchments to changes in both temperature and precipitation while SWAT showed accurate trend for precipitation change only. For temperature change, the SWAT model gave highly irregular results in hydrological trends due to its inconsistency in predicting runoff generated by snowmelt.

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