IMPACTS OF CLIMATE CHANGE ON THE QUANTITY AND TIMING OF RIVER FLOW IN THE UPPER INDUS BASIN, KARAKORAM-HIMALAYA, PAKISTAN

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2021

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（パキスタン国カラコルム・ヒマラヤ山脈インダス川上流域における河川流量と流出時期に及ぼす気候変動の影響）

A dissertation
Submitted in partial fulfillment of the requirements for the
Degree of Doctor of Engineering

By

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Kyoto, 2021

Acknowledgement

First of all, I would like to thanks the Almighty ALLAH for His utmost blessings upon me. He gave me the knowledge and skills to complete this research. Secondly, I would show gratitude to my parents for their sacrifices and support for me.

Last but not least, I would like to express my deepest gratitude to Associate Professor Takahiro Sayama and Professor Kaoru Takara for their enthusiastic guidance, and support for my research and learning. I was encouraged to attend international conferences and symposiums that gave me the new learning opportunities and confidence. I was also financially supported for the data-collection process which made the research easier. I am also thankful to Junior Associate Professor Florence Lahournat for her comments regarding the betterment in the research outputs. Furthermore, comments from Professor Shigenobu Tanaka and Associate Professor Kenji Tanaka were very helpful in improving the quality of the manuscript.

I would like to sincerely acknowledge the role of WAPDA and Meteorological department of Pakistan for providing me with the climate and hydrological dataset for this research. Without their support this research would not have been possible.

A very important contribution and support came for this research from the Japanese Government in the form of MEXT scholarship. This generous scholarship covered all the necessary financial requirements to study in Kyoto University, Japan.

I appreciate the laboratory members for their suggestions throughout the study program. I received positive feedback on the results and help whenever needed. Yamada-san, Sophal-san, Sahu-san, Yamamoto-san and Ichihashi-san were very cooperative during my stay in this laboratory. Special thanks to Saidera-san and Inoue-san for their cooperation, they well-managed all the official and managerial matters pertaining to my stay in the Kyoto University and Japan.

Kyoto University, May 2021

Muhammad Sohaib Baig

Abstract

The Indus river basin holds primary importance in the economy and ecology of Pakistan. It provides water for domestic and irrigation demands. The surface water and groundwater from the Indus river basin are the only source of fresh water supplies to the people of the country. With increasing population and unsustainable utilization of water resources the stress on water from the Indus river has increased in magnitude. This stress has ensued international and national level disputes with the stake-holders. This situation is compounded by several environmental factors like climate and land-use changes. Climate change has been labelled as a serious threat to the fragile eco system of the Indus river basin.

Overall, the Indus river basin is large with considerable climate variabilities within the basin. The upper region attracts more interests because of its abundant water resources, glaciers and hydropower potential. This region holds large mass of glacier that supply water in summer when demands are higher. Also, it receives large sum of snowfall in winter which adds up with glacier melt water and results in higher river flows. This water is very essential for the water demands in the downstream areas where precipitation is less and water-use is higher. Climate change in the future is projected to affect the present water resources both in the timings and quantity. Increasing temperature will play a major role in altering the hydrologic cycle. It will affect the glacier and snow melt process. Precipitation, on the other hand, will increase but with higher spatial-temporal variability. The intense precipitation events will trigger flash floods and landslides. Glacier retreat is another important impact of climate change, the glaciers will continue to lose their mass and their contribution in the annual flows will decrease towards the end of century.

It is necessary to quantify the contribution of glacier, snow and rainfall in the runoff to evaluate the impacts of climate change in the river flows in the upper Indus basin (UIB). APHRODITE climate dataset is used for this analysis because of unavailability of climate data. Degree-day

temperature index models have been employed to calculate the melt from snow and glaciers. The runoff routing is carried out by the Rainfall-Runoff-Inundation (RRI) hydrologic model. Owing to the spatial variability of climate in the UIB, sub-basin hydrology has also been evaluated. This model simulates the river flows in the UIB and estimates the weightage of melt and rain in the stream flow. Furthermore, for future climate impact assessment MRI-AGCM has been employed which has revealed precipitation and temperature patterns in future (2075-2099) climate across the UIB. The hydrologic simulations reveal that currently the glacier melt contribution is the highest among other runoff components. Glacier melt alone contributes almost two-third of the river flows annually. Rainfall and snow fall shares are 12% and 20%, respectively. In future the average temperature will increase to 7.4 °C from 1.77 °C and precipitation will increase to 517 mm/y from 440 mm/y. In future the glacier will lose 72% of their present area because increased temperatures will ensue enhanced melting and mass loss. Overall, the UIB the summer precipitation will increase more than winter precipitation. Temperature on the other hand shows less spatial variability and will increase in every month across UIB. As a result of climate change and glacier retreat, the annual runoff will decrease from 656 mm/y in 1980-2006 to 566 mm/y in 2075-2099 in UIB. Glacier runoff itself will drop to 280 mm/y from 367 mm/y. Even though the summer precipitation will increase, it will not be able to sustain the summer flows. The spring flows in UIB will increase as a result of higher winter precipitation and earlier glacier melt. The changes in the climate will alter the peaks in the hydrographs i.e. snow melt hydrograph will peak a month earlier because of temperature increase.

Owing to the finer spatial resolution the GCM has revealed interesting spatial trends in future climate. Eastern region of the UIB will have higher precipitation in summer while western region will have higher precipitation in winters. Three sub-basins of the UIB investigated in this study shows altered peaks of annual hydrographs because of changes in the climate and glacier cover. Kharmong, located in the eastern edge, shows positive change in the annual hydrograph because of intact glacier cover and increased monsoon rainfall. On the other hand, Shigar and Gilgit will face negative consequences of climate change and glacier retreat. Shigar and Gilgit will lose 56% and 85% of glacier area because of rising temperatures and negative mass balance. Annual hydrograph in both the basins will decrease and pose challenge for the water managers. The impacts of climate change are quantified in another sub-basin, Astore. It is located in the southern region and has an area of 3927 km^2 of which 8% is glacier covered. Under present climate conditions the glaciers are found to contribute one-third of the annual river flows, snow has the highest contribution with 42% followed by rainfall with 25%. The analysis of changing climate on this river basin indicated that by the mid-century (2036-2065) the annual river flows are projected to increase by to 181 m^3/s from 152 m^3/s. This is mainly due to the higher melt of glaciers because of higher temperature and monsoon precipitation. However, in the late century (2066-2095) the annual flows will decrease to 145 m^3/s because of loss in glacier area.

In the last quarter of this century the climate of UIB will become warmer and more precipitation will fall annually. The glacier cover will decrease by three-fourth because of the excessive melting. These changes will cause considerable changes in the regional river flows and result in reduction in the average annual river flows in the UIB. On seasonal basis the spring flows will increase across the UIB and sub-basins because of snow melt and rainfall. Earlier snow and glacier melt in spring will enhance the irrigation potential. In summer the river flows will reduce because of glacier retreat in the UIB and higher precipitation will not be enough to sustain the river flows. This situation can be managed by applying integrated water management systems with UIB and downstream regions.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The Indus river basin covers the area of 1,140,000 km^2 and covers Afghanistan, China, India and Pakistan. The river length is approximately 2,800 km and its origin lies in Tibet and drains its water in the Arabian sea (Figure 1) (Ali, 2013). In the northern parts the basin receives runoff from Himalaya, Karakoram and Hindukush mountains of which more than half consists of melt from snow and glacier (Lutz et al., 2014). The basin supplies essential flows of surface water to one of the world's largest contiguous canal irrigation system (Lutz et al., 2016). Climate in the basin is very variable, with sub-freezing winter temperatures in the north to scorching temperatures in the low-lying areas. In northern areas the average temperatures in summer (May to September) ranges around 15 ◦C while in south this temperature reaches up to 35 ° C. Winter persists from November to February where in northern region the temperatures remain below 0 °C and in low-lying areas it remains between 20-25 °C (Mcsweeney et al., 2012). Precipitation also shows spatial and temporal variability, the northern mountains of Himalaya, Karakoram and Hindukush receives 760 mm to 2000 mm annually. The low-lying area of the basin are arid to semi-arid and receives less than 250 mm of precipitation annually (Chaudhry, 2017). Water demands in the downstream areas due to irrigation and hydropower generation are high and exceeds supply which results in groundwater abstraction and has left the aquifer water-stressed (Gleeson et al., 2012). Cheema et al. (2014) quantified up to 31km^3 of groundwater is depleted annually.

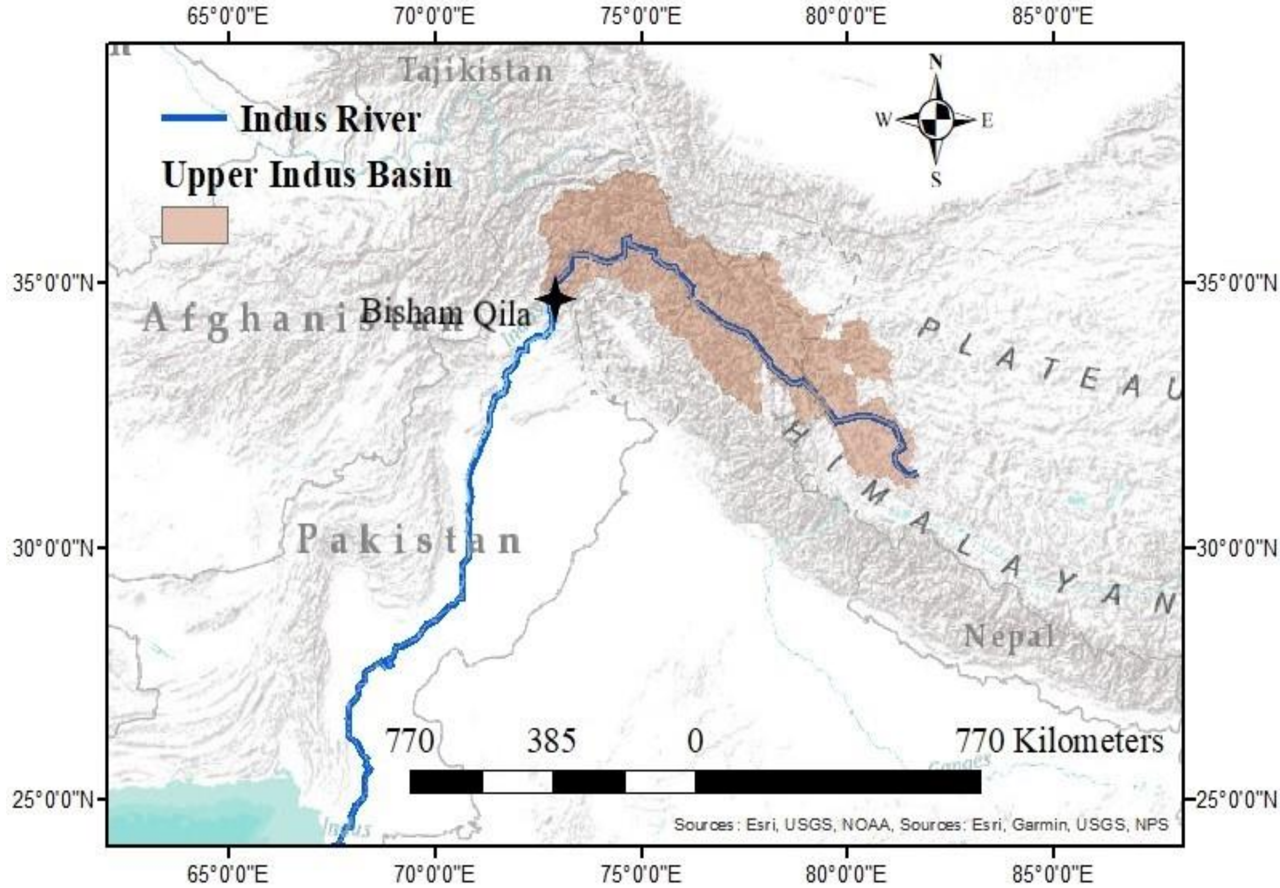

Figure 1: The Indus river and boundary of upper Indus river basin and outlet at Bisham Qila

UIB plays crucial role in sustaining the water demands of the whole Indus river basin. Accurate evaluation of precipitation in the sub-basins of UIB is vital for water resources management, climate change impact studies etc. (Immerzeel et al., 2012). Low-density of precipitation gauges and variation of precipitation over short distances due to orographic influences has posed a challenge to comprehensive precipitation assessment (Dahri et al., 2016). The lack of long-term records of precipitation and temperature in the UIB has resulted in the shift towards gridded datasets. Several researchers have employed theses datasets for quantifying the precipitation and understanding hydrologic cycle. However, these datasets have a downside which is their coarse spatial resolution limiting the performance of the hydrologic models (Lutz et al., 2014).

1.1 PROBLEM STATEMENT AND OBJECTIVES OF THE STUDY

In UIB, the spatial and temporal variations in river flow are very important. Potential impacts of climate change have increased this importance to many folds. The climate variability will affect the timings and quantity of river flows because this region will get warmer than global average (Sanjay et al., 2017, Hasson et al., 2019 & Kraaijenbrink et al., 2017). There is a need to project the future climate and associated river flows of UIB and its sub-basins. Moreover, there is a need to study the shift in the sub-basin hydrology in future. Coarse resolution climate models have been used so far in the region. However, fine resolution climate models have a clear advantage because of their tendency to reveal sub-basin variability in climate. Such analyses are crucial for the futuristic water resources management and water-related hazard risk management. This study focuses on the quantification of runoff components i.e. rain, snow and glacier melt in UIB and its sub-basins. The climate change impacts are estimated using GCMs projections after bias-correction.

The specific objectives of this study are:

1. To set up a hydrologic model to simulate the hydrologic cycle of UIB. This requires employing climate datasets for UIB and available climate datasets for hydrologic modeling. Snow and glacier melt models are used along with geographic datasets i.e. land-use, glacier covers etc. Expected outcomes of this step are calibration of river flows in UIB and quantification of runoff components.
2. To quantify the impacts of climate change on the stream flows of UIB and its sub-basins. This step includes selection and bias-correction of GCM output and glacier cover area in future. The quantification of future climate on river flows will be the last step and require simulation of river flows using GCM output and future glacier area.

1.3 DISSERTATION STRUCTURE

This dissertation is divided into six chapters. First two chapter introduce the background information related to the state of precipitation, temperature, hydrology and climate change in the UIB. They further describe the challenges associated with hydrologic modeling and climate change impacts.

Third chapter describes the methodology employed to simulate the river flows in UIB and subbasins. Snow, glacier melt models and hydrologic models are explained with their processes. Additionally, RRI model is discussed with its input requirements and outputs.

Fourth chapter explains climate change impacts on the Astore river sub-basins of UIB. Simulations use climate data from the weather stations. This is a small sub-basin and climate data from stations has worked well during simulations. Results projected decreasing summer flows in the late century because of glacier retreat.

Fifth chapter explains the datasets used and results achieved. The results describe in details the role of precipitation, temperature and glacier in the runoff. Furthermore, future climate change scenario is discussed, its bias and its correction process are explained. In the last part the impacts of climate change on river flows are explained with the help of graphs and figures.

Last chapter concludes the whole thesis. It discusses the methodology, its merits and shortcomings. Followed by the results and future directions.

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CHAPTER 2: LITERATURE REVIEW

2.1 REVIEWS OF STUDIES ABOUT PRESENT CLIMATE AND RUNOFF IN THE UIB

Several attempts have been made to correct the precipitation and temperature in the high mountainous regions. Observed climate data, satellite derived products and climate model outputs have been employed to quantify the spatio-temporal patterns of precipitation and temperature. The Hunza river basin is a sub-basin of UIB (Figure 1), its location in the central Karakoram range makes it an ideal region to study the climatic conditions. It is 14,234 km^2 in area and elevation ranges from 1394 m to 7849 m. The glacier cover is 3930 km^2 while snow cover at the end of winter precipitation is around 80% (Tahir et al., 2011). The sub-basin has a complex precipitation regime, in summer (June to September) monsoon brings rainfall. On the other hand, winter precipitation is the result of the depression that comes from the west. This westerly depression provide the vital nourishment for the glaciers in the region (Young & Hewitt, 1990). Immerzeel et al. (2012) used glacier mass balance to quantify the spatial distribution of precipitation in this sub-basin. They assumed neutral glacier mass balance for three years from 2001 to 2003 and used reverse modeling to estimate the precipitation. The results indicate a strong under representation of precipitation at the higher elevation. The total precipitation in the sub-basin is estimated to be 828 mm/year which is much higher than average of the three climate stations' (319 mm/year). Precipitation increases with the rate of 0.21 % ± 0.12 % m^{-1} till the elevation of 5500 m and decreases above that elevation.

Furthering the previous research from a sub-basin to the whole UIB, Immerzeel et al. (2015) reported that precipitation is under reported in the neighboring river basins as well. In order to calculate the precipitation and temperature in the whole region they selected APHRODITE climate dataset from (Yatagai et al., 2012). This dataset has depicted temporal and spatial trends in precipitation in a better way and has finer spatial-temporal resolution (Lutz et al., 2014b). Study covered the Karakoram-Hindukush-Himalaya mountainous regions with an area of 4.37×10^5 km^2. The authors noted that amount of precipitation required to sustain the glaciers' mass is far below the recorded precipitation at the climate stations. Furthermore, the water balance of the region could only be justified if the precipitation at higher elevations is twice as high or in some cases up to ten times of the available precipitation records. A glacier-mass balance model is used to simulate observed glacier-mass balance. Overall 550 glaciers with in the UIB have been selected and vertical precipitation extrapolation rate is estimated for each glacier. The precipitation extrapolation rates then spatially interpolated to represent the altitude dependence of precipitation. Spatially interpolated precipitation extrapolation rate is used to update the APHRODITE precipitation data. Finally, updated precipitation is found to be 913 ± 323 mm annually which is twice more than original APHRODITE estimate of 437 mm. A direct relation between elevation and precipitation is established throughout the region albeit with different magnitudes. The median extrapolation precipitation rates for Karakoram is 0.12% m^{-1}, Hindukush is 0.26% m^{-1} and for Himalaya is 0.044% m^{-1}.

Reggiani and Rientjes (2015) estimated the water-balance of UIB by using river flows and precipitation data. The equation consisted of precipitation subtracted by evaporation, deep-groundwater recharge and runoff. They analyzed long-term river flows, available precipitation and evaporation data to quantify the variables of water-balance equation. The available precipitation datasets are not suitable owing to their low-density and low altitude. Additionally, satellite imagery and atmospheric re-analysis datasets have also been employed to overcome this issue. The average annual precipitation is estimated to be 681 ± 100 mm. Actual evaporation records do not exist therefore based upon actual evaporation estimates from Bhutiyani (1999) actual evaporation in the basin is assumed to be in the range of 200 ± 100 mm/year. The runoff in the basin at Bisham Qila is 2380 m^3/s which corresponds to 456 mm annually which when added with evaporation balances the equation.

Dahri et al. (2018) used an advances water-balance equating technique to correct the precipitation in the UIB. Their results depict more spatially and temporally distributed precipitation and temperature estimates. The authors employed simple methods to adjust errors in the precipitation as recommended by WMO. Also, techniques to adjust snow accumulation and river flows are introduced. The expression to account for the errors in the precipitation is shown in (Equation 1).

$$P_a = (1 - R)K_r(P_m + \Delta P_{wr} + \Delta P_{tr} + \Delta P_{er}) + RK_s(P_m + \Delta P_{ws} + \Delta P_{ts} + \Delta P_{es}) \qquad (1)$$

where P_a is adjusted precipitation (mm), R is the proportion of snow in precipitation, K_r is correction factor for wind-induced losses (mm), P_m is measured precipitation (mm), ΔP_w is wetting losses (mm) and ΔP_t is trace precipitation (mm) and ΔP_e is evaporation losses. The subscripts s and r represent snowfall and rainfall respectively. In total, 328 precipitation stations are included in the study. After error-adjustment monthly averaged precipitation is interpolated over the entire UIB. This adjusted precipitation is found to be much higher than actually recorded one where as overall range of correction is between 12 to 773 mm annually. Wind is found to be causing largest errors in precipitation among all the sources and underestimate in snowfall was found to be greater than rainfall. For entire UIB the increment of 21.3% is suggested in the average precipitation. Precipitation in the northern sub-basins was highly under recorded such as 46% increase in Hunza, 36% in Gilgit and up to 77% in Shyok river basin was recommended.

Another study by Khan and Koch (2018) employed this precipitation correction albeit with addition of vertical precipitation rate. Similar background of errors in precipitation data is explained to justify application of correction methods explained in (Equation 1). the precipitation extrapolation rate is defined as

$$P_{rate} = (Q + ET + g - P_{obs}) / \Delta h \quad (2)$$

where P_{rate} is the precipitation extrapolation rate (m^{-1}), Q is the river runoff, ET is the actual evapo-transpiration, g is losses/gain in the glacier volume, P_{obs} is the observed precipitation and Δh is the difference between mean elevation of catchment and observation network. Regional glacier mass balances estimates are derived from Gardelle et al. (2013), Tahir et al. (2016) and Scherler et al. (2011). For entire UIB the glacier gain of 7.87 mm/year is selected, however in upstream of Kharmong glacier loss of -16.82 mm/year is used. The corrected precipitation for UIB is approximately 608 mm/year.

In high altitude regions where melt runoff from snow and ice contributes in the streamflows, understanding of hydrologic conditions requires information of altitudinal temperature variation (Mukhopadhyay & Khan, 2017). In such catchments temperature lapse rate play important role in the hydrology. Temperature lapse rates depend upon dry (-0.0098 ◦C m^{-1}) and saturated (-0.005 ◦C m^{-1}) adiabatic lapse rate (Immerzeel et al., 2015). As explained in the previous section that APHRODITE product faces issues in mountainous region due to lack of representative climate stations. The inherent bias in the temperature dataset underestimated the winter temperatures and overestimated the summer temperatures. A correction method applied on APHRODITE temperature dataset over entire UIB by Lutz et al. (2014) includes:

- Elevation dependent temperature lapse rates are used to correct the APHRODITE dataset
- Bias between observed and APHRODITE dataset is calculated
- Monthly relation between bias and elevation is established
- Finally, APHRODITE temperature is corrected using bias-elevation relation

For each day in the original APHRODITE dataset, for each grid cell the following correction is applied:

$$T_{COR(x,y)} = T_{APHRO(x,y)} + a.H_{(x,y)} + b \quad (3)$$

where T_{COR} is corrected temperature, T_{APHRO} is the actual APHRODITE data, H is the grid cell elevation, a and b are monthly coefficients representing bias between temperature and elevation. The corrected temperature in the UIB shows that in original dataset the region upstream of Kharmong had bias ranging -4 to -5 ◦C. In Shyok subbasins mean annual temperature remains between 0 and -5 ◦C.

Temperature varies with elevation because of change in air-pressure, this change in temperature is called as adiabatic lapse rate. Along with elevation, latitude also affects temperature, however the magnitude differs in tropics, polar and temperate regions. Despite this, latitude is often neglected in temperature studies. In their study Dahri et al. (2018) estimated temperatures in UIB using altitude and latitude. The results confirmed the relation between latitude and temperature-variation albeit less strong than elevation. Inclusion of latitude as a predictor improvers the correlation of regression models up to 6% for maximum temperature and up to 1.5% for minimum temperatures. Mukhopadhyay and Khan (2017) reported that in the sub-basins of UIB the maximum temperature occurs in July except for Hunza basin where August temperatures are higher. The temperature lapse rates increase from January to April and remain constant in the following months up till September. The decline in lapse rates starts from October and continues in winter. It could be implied that largest altitudinal temperature variation takes place during snow and ice melt season. An interesting aspect of the elevation-temperature relation is the altitude where freezing temperature prevails (i.e. 0 ◦C). This altitude depends upon temperature and lapse rate and varies seasonally. Maximum altitude occurs in July and August, in July it varies between 5200 and 6300 m while in August the range is 5300 and 6200 m. Overall in UIB the lowest altitude of 0 ◦C-temperature is between 1800 and 2800m. throughout the UIB variation in the altitude is controlled by humidity and terrain characteristics.

Runoff in the UIB consists of rainfall, snow and glacier melt, the peak flows occur in summer when snow and glacier melt (Lutz et al., 2014). In the downstream of Bisham Qila (Figure 1) a large a large reservoir, Tarbela is located, which supplies essential water for irrigation, store flood water and generate hydropower (Lutz et al., 2016). The UIB hosts large mass of glaciers and receive heavy snowfall in winter whose contribution have been estimated by several studies. Archer, (2003) reported three sources of runoff generation in UIB, melt water from glaciers in the high altitude catchments, seasonal snow melt and rainfall during summer monsoon. Mukhopadhyay and Khan (2014) quantified the components of runoff in UIB by hydrograph separation technique. They explained the contribution from sub-basins according to both elevation and season. Elevation play important role in the quantity of runoff be it melt water or rainfall. Precipitation is negligible below 2500 m and runoff contribution is lower. However seasonal snow in winter between the elevation of 2500 and 3500 m generate high melt water. The elevation band of 5000 and 6000 m is represented as the high precipitation zone, precipitation here also nourishes glaciers. In summer (July to September) this snow melts. The melt water between the elevation of 4500m and 6500m consists of glacier and snow melt. The glacier melt contribution from Shigar, Shyok and Hunza sub-basins vary from 31-35% while snow melt’s weightage is 41-43%. Astore river receives quite less runoff from glacier melt (18%) and 50% of its runoff consists of snow melt. In upstream region, at Kahrmong glacier and snow melt contributions are 22 and 44% respectively. At Bisham Qila, this contribution of glacier and snow melt becomes 21 and 49%. Annual hydrograph shows low flows from January to April, streamflows start to rise from May and reaching maximum level in July/August. These high flows persist in September and starts to fall down in October. There is a variability of flow peaks among sub-basins, like in Yogo the higher flows are in August rather than July. Overall, annual flow regime is divided into four components, October to December (L1), January to March (L2), April to June (H1) and July to September (H4). In H1 the streamflow mainly consists of melt water from seasonal snow below 3500 m. while H2 consists of melt water glaciers, ice packs and monsoon rainfall between 3500 and 5500 m. In order of their weightage the components could be arranged as H2 > H1 > L1 > L2. At each station 82% of annual flow comes between May-September. During July and August 40-60% of flow originates and in August to September 30-44% flow is generated. From the elevation band between 3500-5500m, in Shyok, Shigar and Hunza sub-basins the runoff surpasses the runoff from low elevation band 2,500m-3,500m. While in Gilgit an opposite behavior is observed. In Astore sub-basin, located at the western edge of Himalayan range, runoff from elevation band of 3500-5500m is slightly higher than 2500-3500m. At Bisham Qila the 3500-5500m elevation zone contributes 41% and other elevation zone's contribution reaches at 29%. In the downstream of the UIB, during H1 20-31% of streamflow comes from Shigar, Shyok and Hunza sub-basins due to their greater snow cover areas. During H2 these three sub-basins contribute ~50% flows at the downstream. During L1 and L2 these sub-basins contribute one-third to the total flows at the downstream (Mukhopadhyay & Khan, 2014).

2.2 REVIEWS OF CLIMATE CHANGE IMPACT STUDIES IN THE UIB

In the previous sub-sections, the trends in temperature and precipitation and their impact on streamflows are discussed. Glacier are found to play a significant role in the river flow in summer along with monsoon rainfall and seasonal snow melt. UIB consists of Himalaya-Karakoram-Hindukush mountain regions which is quite vulnerable to climate change and variability. Since most of the global warming in the past decades is attributed to the greenhouse gas concentrations in atmosphere, regional cryosphere and hydrologic processes are under stress from warming climate (Wester et al., 2019). Potential impacts of changing climate and variability in UIB has attracted many researchers. Several studies have tried to quantify the future changes in the climate and water balance of UIB. Rising temperature will cause more water to evaporate which in return increase the moisture content in the atmosphere rendering spatio-temporal precipitation more variable. In addition to the precipitation variability the increased temperature will alter the hydrologic cycle in UIB because runoff largely depends upon melt from snow and glaciers (Immerzeel et al., 2010).

Fowler and Archer (2006) studied temperature trends in the UIB for 1961-2000 and reported contrasting seasonal and diurnal trends. The seasonal trends in temperature show decreasing summer temperatures and increasing winter temperatures. Moreover, summer temperature's decrease combined with positive trend in winter precipitation signal at reduced ablation rates in Karakoram region. Linear relation between summer temperature and runoff in Hunza predicted 20% reduction in river flows during 1961-2000. This reduced ablation trend is strengthened by observed expansion of glaciers in UIB. Another striking finding of the study is the increasing diurnal temperature range. Maximum and minimum temperature at Gilgit and Skardu stations indicate that this increase in the range started somewhere in the mid of twentieth century. Their study stated that temperatures at the valley stations can be used to estimate temperature at the higher altitudes and with the help of regression analysis runoff projections can be made.

A research to study the variability in temperature and precipitation over Pakistan is conducted by Saeed and Athar (2018). Their research focused on IPCC's fourth assessment report and reported changes in temperature and precipitation over Pakistan. Three scenarios namely A2, A1B and B1 are used for future projections. The future time period is divided into three individual periods, 2025-2049, 2050-2074 and 2075-2099. For brevity the results for northern Pakistan are presented in (Table 1).

Table 1: Change in temperature and precipitation in future (Saeed & Athar, 2018)

Future period	Precipitation (%)		Temperature (°C)	
	Winter	Summer	Winter	Summer
2025-2049	-1.7 (-9.4 ~ 9.6)	8.04 (-3.3 ~ 25.3)	1.6 (1.4 ~ 2.3)	1.6 (1.3 ~ 2.2)
2050-2074	-5.8 (-14.5 ~ 5.6)	17.8 (-0.6 ~ 30.0)	3.2 (2.5 ~ 3.6)	2.7 (2.3 ~ 3.7)
2075-2099	-7.7 (-15.4 ~ 4.7)	21.3 (-8.6 ~ 36.6)	3.9 (3.1 ~ 4.6)	3.7 (3.0 ~ 5.0)

A consistent increase in the temperature is projected from 2025 onwards in both the seasons, with more warming in winter season. Up to 4 °C warming is expected as compared to current temperatures. precipitation will show interannual variability by decreasing in winters and increasing in summer. The summer monsoon season will bring heavy rainfall in the region but spring river flows will decrease due to less winter precipitation. Moreover, this less winter precipitation will affect the glacier nourishment in the northern Pakistan.

Downscaling of GCMs is important to study the regional dependency and variability of climate. These downscaled projections play important role in planning for future in Pakistan where complex topography, influence of different weather phenomenon etc. has made it difficult. Kazmi et al. (2015) used statistical downscaling to project the future climate of Pakistan and reported that northern region would become vulnerable to increasing temperatures. This temperature increase will affect the cryo-hydro process but environmental conditions of the region may be at risk. Overall 44 climatic stations are involved in the analysis along with HadCM3 GCM. Two future scenarios namely A2 and B2 are used to study the temperature changes (Table 2):

Table 2: Range of temperature and precipitation in future (Kazmi et al. 2015)

Future period	**Minimum temperatures (°C)**		**Maximum temperatures (°C)**	
	A2	**B2**	**A2**	**B2**
2001-2010	-1.0 ~ 0.5	0 ~ 0.5	0 ~ 0.5	0.5 ~ 1
2011-2020	0.5 ~ 1.5	0 ~ 1	0.5 ~ 1	0.5 ~ 1
2021-2030	0.5 ~ 1	0 ~ 1	1 ~ 2	1 ~ 1.5

A2 scenario is found to be showing larger range of temperature variability over the northern Pakistan. In B2 the minimum and maximum temperature will vary between 0 to 1.5 °C. While, A2 projects a wider range of temperature variation of -1 °C to 2 °C. A2 also subtle decrease in minimum temperatures in first decade of the century. But this decrease in temperature is limited over a smaller area in the region.

On the contrary in future the average temperatures are going to increase albeit with different rates. Several studies have projected change in the temperatures by the mid and end of twenty-first century. Sanjay et al. (2017) used dynamically downscaled regional climate model projections to evaluate the future climatic conditions across HKH region under RCP 4.5 and 8.5. Future is divided into two periods, near future (2036-65) and far future (2066-95). In the HKH region encompassing UIB in near future (RCP 4.5) summer and winter temperatures will increase by 2 °C and 2.3 °C respectively. This range increases towards the end of century by 2.6 °C and 3.1 °C respectively. Since RCP 8.5 is high emission scenario it has projected higher temperatures in comparison. In near future the temperature in summer and winter will be 2.7 °C to 3.2 °C. In far future this increases almost two folds from near future to 4.9 °C and 5.4 °C in summer and winter respectively. On the other hand, precipitation also increases except in one scenario. In RCP 4.5 near future the precipitation is shown to decrease by a slight margin of 0.1% in summer, in winter this will increase by 7%. Similarly, in far future the change in precipitation in summer and winter is respectively 3.5 and 14.1%. this 14.1% increase is the highest quantity of precipitation change projected by the RCMs. In RCP 8.5, under near future the summer and winter precipitation will increase by 3.5% and 12.8%. in far future this range remains almost unchanged with 3.9% and 12.9%.

The glaciers in the UIB are separately studied for their behavior against climate change. The projected retreat of glacier in UIB will ensue unprecedented stress on already fragile water resources. In an attempt to analyze future glacier mass due to climate change Huss and Hock (2015) developed a glacier mass balance model. The model consists of balance of snow accumulation, snow and ice melt and refreezing. The model is calibrated and validated with ERA-Interim climate data. Following this, the model is run with downscaled climate data from 14 GCMs. Under RCP 4.5 glacier area in the UIB is projected to decrease by 70% and up to 80% under RCP 8.5. This glacier retreat in UIB is equivalent to sea-level rise of 5 to 7 mm.

Figure 2 shows decrease in glacier area in the south-west Asia, of which UIB is a part, under RCP 8.5. all GCMs concur on decreasing glacier area but with different magnitudes. These differences could be attributed to different climate projections. GCM GFDL-CM3 shows largest reduction in the area, according to simulations the remaining area will be 1052 km^2 which is 3.4% of the glacier area in 2010. CNRM-CM5 projected least decrease in glacier area with 50% reduction.

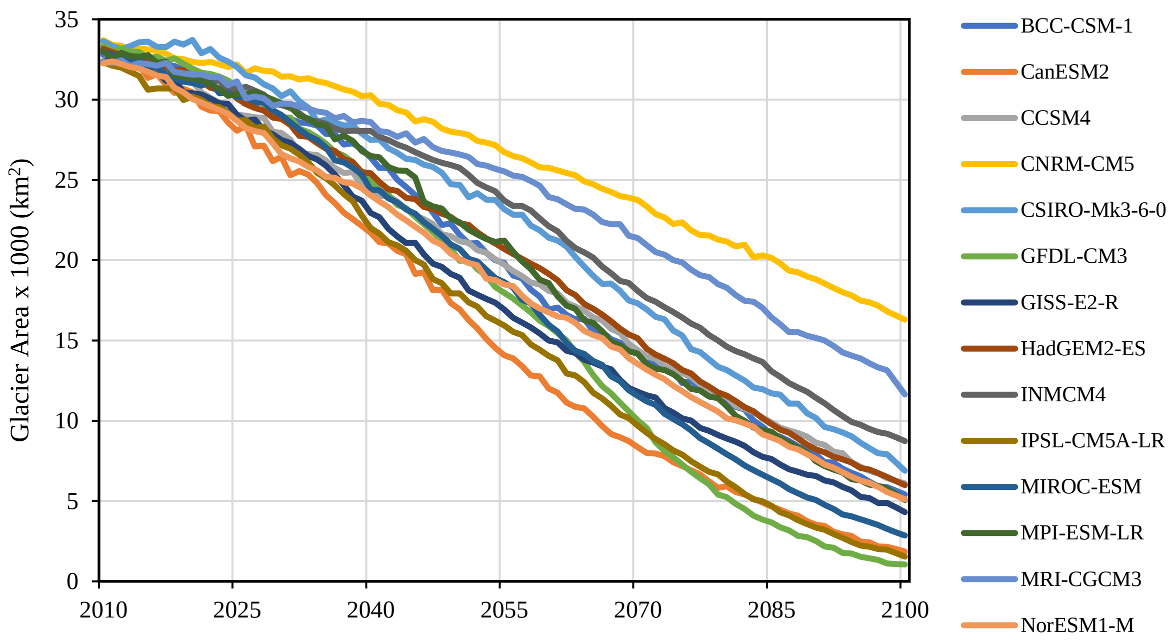

Figure 2: Changes in glacier area in future according to 14 GCMs (Huss & Hock, 2015)

Advancing the previous glacier mass balance study Rounce et al. (2020) simulated the contribution of glacier runoff throughout 21st century. In total, 22 GCMs have been selected with four RCPs ranging from 2.6 4.5, 6.0 and 8.5. Keeping in mind the retreating glacier cover the runoff divided into two components i.e. fixed-gauge and moving gauge runoff. Moving gauge runoff is the runoff measured at the gauge which moves with the retreating terminus of glacier. Fixed-gauge is defined as the sum of moving-gauge runoff and runoff generating from previously ice-free area. Equations (4) and (5) explain both runoffs in mathematical form.

$$\text{moving gauge runoff} = \text{runoff from the changing glacier area} \qquad (4)$$

$$\text{Fixed gauge runoff} = \text{moving} - \text{gauge runoff} + \text{runoff from the initial glacier area} \qquad (5)$$

It is generally understood that increasing temperatures will enhance glacier melt rates. The enhances melt rates will initially contribute more in the river flows but at a certain instance the beyond which the runoff will start to decline. This instance is referred as peak water. Peak water is spatially variable and depends upon future climate. In UIB under RCP 8.5 the peak water is expected to occur between 2065-2075. Up till peak water occurrence the fixed glacier runoff is projected to increase by 40% from 2000-2015. From the peak water instance till 2100 in Indus river basin the fixed-gauge glacier runoff will decrease but it will still remain above the present values. Change in monthly fixed-gauge glacier runoff in summer (June to September) with respect to present values (2000-2015). Table 3 shows the change in the monthly river flows in the end of century 2085-2100 with respect to 2000-2015 under all RCPs. June shows increase in all RCPs and August is projected to show opposite trend. Maximum increase occurs in June (+103) under RCP 8.5. Across all RCPs August shows decrease in flows probably because during that time of the year the glacier is limited to higher elevations and lesser melt is generated.

Table 3: Projected change in the glacier runoff in summer (2085-2100) (Rounce et al. 2020)

RCP	**ΔQ_{Jun}**	**ΔQ_{July}**	**ΔQ_{Aug}**	**ΔQ_{Sep}**
2.6	+10±12	-12±6	-23±5	-20±7
4.5	+53±15	-3±7	-17±6	-2±9
6.0	+82±19	+8±8	-7±6	+21±12
8.5	+103±22	+2±8	-7±7	+69±18

River flows from UIB are vital for the ecology and demands in the downstream areas. The expected change in the hydrologic characteristics are important for sustainable water management. Lutz et al. (2016) used ensemble of statistically downscaled CMIP5 GCM outputs for RCP 4.5 and RCP 8.5 in UIB to evaluate the impacts of climate change on river flows. The hydrologic model used in the study includes detailed physical processes pertaining to cryosphere, soil-water interaction etc. Table 4 explains the projected climate in the future used in the study.

Table 4: Summary of GCMs and change in climate scenarios (Lutz et al. 2015)

RCP	**GCM**	**Change in temperature (°C)**	**Change in precipitation (%)**
RCP 4.5	inmcm4_r1i1p1	2.1	-4.6
	IPSL-CM5A-LR_r3i1p1	4.3	-6.3
	MRI-CGCM3_r1i1p1	2.5	10.5
	CanESM2_r4i1p1	4.4	13.2
RCP 8.5	MPI-ESM-LR_r1i1p1	6.0	-7.9
	IPSL-CM5A-LR_r3i1p1	8.0	-10.2
	CSIRO-Mk3-6-0_r1i1p1	5.6	29.8
	MIROC5_r3i1p1	6.7	31.0

Temperature increase is projected to be in the range of 2.0 to 8 °C. The northeastern part of UIB will get more warm than other parts in both RCPs. Significantly strong warming difference of ~1 °C to ~2 °C is projected between higher and lower altitudes where as high altitudes will become warmer. Precipitation is highly variable, decreasing and increasing in four scenarios each. The decrease in precipitation is relatively smaller as compared to the increase. Mean annual precipitation trend suggests monsoon intensity will increase in southeastern parts of UIB. On monthly basis decrease in precipitation is projected for February-March and increase is projected during October. For future glacier mass change a glacier mass balance model is forced with present climate and calibrated. The future climate data is used to simulate future changes in the glacier mass before simulating future hydrologic conditions. Glacier in the region will lose up to 35% to 87% of their current mass. Present components of runoff are divided into glacier, snow, rainfall and baseflow. Glacier melt's weightage is highest in Hunza (85%) and Shigar (43%) basins thus making this component highest among others with 55% annual share in UIB. This larger share of glacier melt is estimated to decrease in future across all scenarios due to reduced glacier area, snow melt will surpass it because of higher winter precipitation. An important change in the form of precipitation in future is increase in the proportion of rainfall as compared to snowfall. Currently rainfall is 58% which will increase to 66% under RCP 4.5 and 75% under RCP 8.5. Even though proportion of rainfall increases in future but snow melt contribution does not decrease. The possible explanation lies in reduced sublimation due to reduced snow cover area or increased evapotranspiration. In a nutshell, in the end of this century:

- the water availability from UIB will be in the range of -15% to 60%,
- in near future (2021-2050) the summer flows will increase slightly and spring flows will increase higher in proportion due to higher precipitation.
- In far future (2071-2100) the summer flows will decrease with stronger increase in spring flows
- Intensity and frequency of extreme discharge will increase implying floods events in the coming decades

Climate change impact studies have also focused on smaller sub-basins of UIB as well. For instance, in UIB, Hunza, Shigar and Shyok river basins climate and cryosphere change impacts on river flows have been studied. These studies shed light on the spatial variability on the regional hydrologic cycle, runoff components and existing climate along with future water availability. Table 5 shows effects of climate and cryosphere change in the Hunza and Shyok river basins of UIB.

Table 5: Summary of climate change and their impacts in river flows of sub-basins

Hunza[1]	**Results**	**Shyok[2]**	**Results**
20% increase in cryosphere until 2075 and 10% increase until 2025	7% and 14% increase in mean summer discharge	The snow cover area will increase up to 10% by 2050, 20% by 2075	11% and 20% increase in mean summer discharge
4 °C increase in mean temperature till 2075, 3 °C increase till 2050 and 2 °C increase by 2025	64%, 100% increase in mean summer discharge	Mean temperature will increase by 1 °C till 2025, 2 °C till 2050, 3 °C by 2075 and 4 °C by 2100	26%, 54%, 81% and 114% increase in mean summer discharge
A 2-4 °C increase in mean temperature with respect to elevation in descending order with increasing elevation	100% increase in mean summer discharge	Average increase of 3 °C with 20% increased snow cover area by 2075	118% increase in mean summer discharge

[1] (Tahir et al., 2011) and [2] (Tahir et al., 2019)

The results from both the basin are quite straightforward and show increasing water flows. this is due to the increased winter precipitation causing snow cover area to increase producing more melt water in spring and summer. Another factor is temperature increase, which will enhance the melt water from the snow cover area, currently 33% (Hunza) and 30% (Shyok) of the basin area are snow-covered, and higher temperatures are directly related to the increasing melt rates. An important aspect of temperature increase is the disappearing of the glaciers in the basins because of excessive melt. the author of the studies recommends building of reservoirs to store the increasing flow of water for irrigation and domestic demands.

In Shigar river basin, a glacio-hydrological basin is used by Soncini et al. (2015). The model considers the physical and climatic process pertaining glacier dynamics. The basin has 6920 km^2, glacier cover is 2164 km^2, elevation range is 8561 ~ 2142 m and stream length is 125 km. Annual average discharge is 203 m^3/s, melt water from snow and ice is the major contributor while monsoon rainfall have little contribution annually. In May the melt component starts to rise with 54% snow and 22% glacier melt. this higher snow and less glacier melt proportion continues in June as well. But, in July and August the snow melt decreases in comparison of glacier melt. In July and August and September glacier contributes 58, 74 and 87% alone, this dominance continues in October with 70%. For climate change impacts three GCMs have been selected, namely EC-Earth, ECHAM6 and CCSM4. The climate change will alter the hydrology of the basin, in most of the cases the runoff will increase until the end of the century before decreasing due to loss of glacier. Higher projected precipitation will not be enough to sustain the mass-loss of the glaciers, this will result in floods, glacial lake outbursts etc. in coming decades. The expected changes in the climate of the basin are expressed in the Table 6, precipitation change is shown in %, whereas temperature change is shown in °C. Temperature changes of three GCMs are quite similar, with almost same values in RCP 4.5 and 8.5. On the other hand, EC-Earth has projected more precipitation where as other two GCMs have shown mixed precipitation projections with little variations.

Table 6: Summary of GCMs and their projections for Shigar river basin (Soncini et al. 2015). Increase in temperature and precipitation are shown in (°C) and (%) respectively.

Future period	EC-Earth		CCSM		ECHAM6	
	RCP 4.5	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Temperature 2040-49	1.18	1.73	1.80	2.24	1.59	1.73
Precipitation 2040-49	11.9	16.3	-5.9	-5.6	4.8	-5.4
Temperature 2090-99	3.0	5.36	2.31	5.09	2.63	5.69
Precipitation 2090-99	8.4	30.5	2.1	6.6	10.5	0.2

Simulation of ice has shown that under RCP 4.5 in 2040-49 ice mass will undergo a slight decrease and in 2090-99 it will decrease up to two-third of the current mass. Similarly, under RCP 8.5 the ice mass in 2040-49 will decrease by a little margin but in 2090-99 a reduction in the range of 80 to 90% is expected.

This change in ice mass and climate is well represented by simulated hydrographs for the future. In last decade under both RCPs the summer flows will decrease due to reduced ice contribution. Currently in August the average flows are ~ 700 m^3/s but it will be around 650 m^3/s under RCP 4.5 and 600 m^3/s under RCP 8.5. Across all GCMs, in the decade of 2040-49 the August flows will remain higher with little margin. Across all GCMs, the spring flows are shown to increase from present flows due to higher precipitation and early glacier melt. Presently, April and May flows are ~ 100 m^3/s but they are expected to rise up to ~ 300 m^3/s.

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CHAPTER 3: HYDROLOGIC MODELING OF UIB

3.1 HYDROLOGIC MODELING

The grid-based model based on the Rainfall-Runoff-Inundation (RRI) model introduced below is run with snow and glacier melt models. The rainfall, snow melt and glacier melt is calculated for each grid and used for simulating river flows. for snow and glacier melt degree-day melt models are used. These models require daily precipitation, temperature and topographic information. A flowchart explaining the modeling process is shown in (Figure 3).

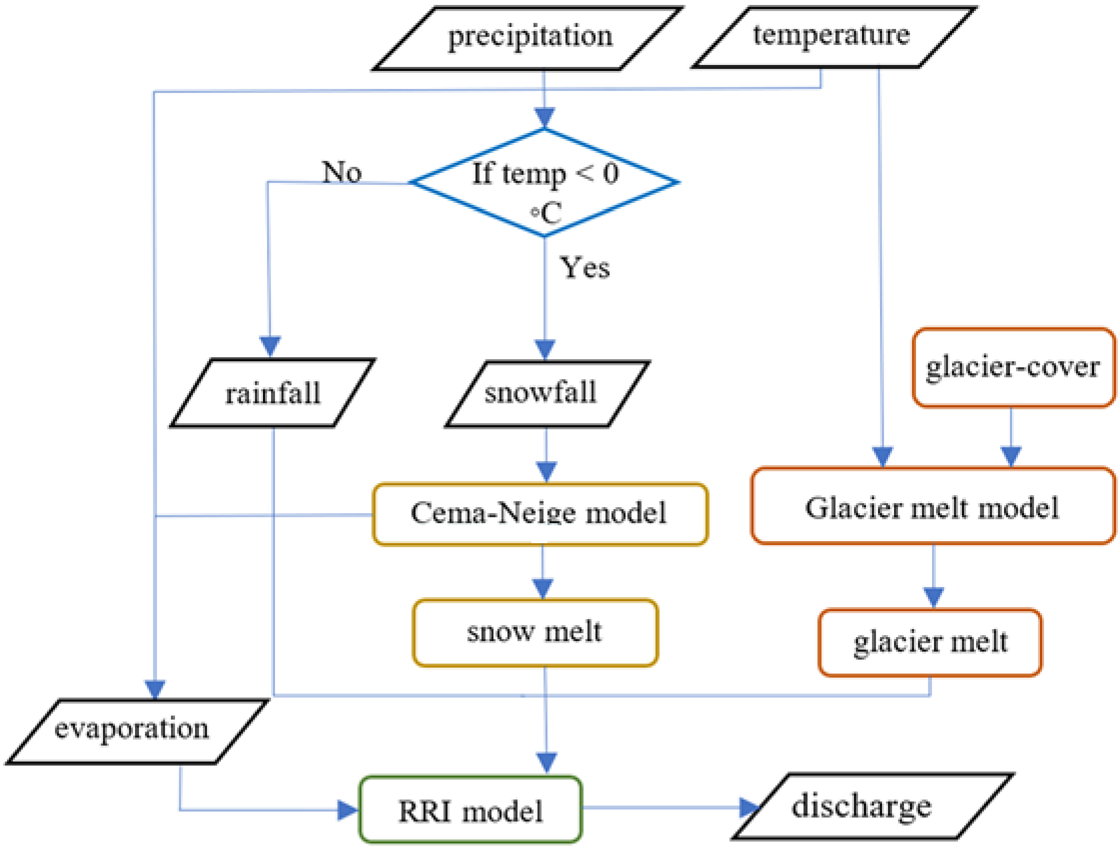

Figure 3: Flowchart of the research methodology and data sources.

3.2.1 CEMA-NEIGE SNOW MODEL

Snow melt model has been adopted from Valéry et al. (2014). This is a degree-day melt model and uses maximum (T_{max}), minimum (T_{min}), and mean air temperatures (T_{mean}), to distinguish between rainfall and snowfall. It has additional feature of calculating the percentage of snow (P_s) in precipitation.

If the maximum temperature is below 0 ◦C, all precipitation is considered snow i.e. 100%. If minimum temperature is above 0 ◦C all precipitation is rainfall. In all other cases the percentage is estimated by employing the third expression in the Equation (6).

$$P_s = \begin{cases} 100\ \%\ if\ \ T_{max} < 0°C \\ 0\ \ if\ T_{min} >\ 0°C \\ 1 - \dfrac{T_{max}}{T_{max}\ -\ T_{min}} \end{cases} \qquad (6)$$

The quantity if rainfall and snowfall is calculated by the Equations (7) and (8).

$$P_{snow} = P_s\ x\ P \qquad (7)$$

$$P_{rain} = P - P_{snow} \qquad (8)$$

where P_{snow} is snow precipitation (mm/d), P is precipitation (mm/d) and P_{rain} is liquid precipitation (mm/d). Snow pack temperature ($Snowpack_{temp,t}$) defines internal thermal state of the snow pack which is used to quantify the melt. If the internal temperature rises to 0 ◦C the melt takes place. Equation (9) estimates the snowpack temperature.

$$Snowpack_{temp,t}\ =\ \min\begin{cases} 0 \\ X * Snowpack_{temp\ t-1} + (1 - X) *\ T_{mean} \end{cases} \qquad (9)$$

where $Snowpack_{temp,t}$ is snow pack temperature ◦C and X is snow pack inertia factor which is set by calibration. Potential melt, $Melt_{pot}$ (mm/d), is computed when snowpack temperature reaches 0 ◦C and mean air temperature is greater than 0 ◦C (Equation 10).

$$Melt_{pot} = ddf * T_{mean} \qquad (10)$$

where *ddf* is degree-day factor. Melt cannot exceed snow storage. In such case the $Melt_{pot}$ is restricted to snow storage. Accumulation of snowfall is an important part of Cema-Neige model. The accumulation is updated daily based on the previously stored snow and the sum of P_{snow} of the particular day (Equation 11).

$$SS_{update} = SS_{update,t-i} + P_{snow,t} - Melt_{act} \quad (11)$$

where SS_{update} (mm) is snow storage update after accumulation and melt of snow, *SS* is snow storage (mm) and $Melt_{act}$ is actual melt (mm/day). Actual Melt, $Melt_{act}$ (mm/d), is estimated by an empirical expression (Equation 12). The snow cover area is also employed in this function.

$$Melt_{act} = (0.9 * snow\ cover\ area + 0.1) * Melt_{pot} \qquad (12)$$

Snow covered area (%) is a unique and simple feature of the model. The model uses P_{snow} and annual average snowfall to estimate the percentage of the river basin covered with snow (Equation 13).

$$snow\ cover\ area = \begin{cases} SS_t/Z & if \quad SS_t < 0.9 * Z \\ & 1 \end{cases} \qquad (13)$$

where *Z* is average annual snow precipitation (mm).

3.2.2 GLACIER MELT MODEL

The glacier's cover of the region estimated by ICIMOD (2011) has been used to calculate the melt from each grid. The glacier melt is quantified using a degree-day model explained by Terink et al. (2015). Equation (14) is used to calculate daily melt from clean ice and debris-covered glaciers.

$$A_{CI/DC} = \begin{cases} T_{avg} \,.\, DDF_{\frac{CI}{DC}} \,.\, F_{\frac{CI}{DC}} & if \quad T_{avg} > 0 \\ 0 & if \quad T_{avg} \leq 0 \end{cases} \quad (14)$$

In the above equation $A_{CI/DC}$ refers to daily glacier melt from clean ice and debris covered glaciers, $DDF_{CI/DC}$ (mm C^{-1} day^{-1}) are degree day factors respectively and $F_{CI/DC}$ are the proportion of clean ice and debris covered glaciers in the grid. The degree day factors are set by calibration. The total glacier melt is the sum of both $A_{CI/DC}$ (Equation 15).

$$A_{GLAC} = (A_{CI} + A_{DC}) \quad (15)$$

3.2.3 RRI MODEL

The runoff generated from the Cema-Neige model for snow melt and the above described glacier melt model is used as the input for the RRI model. The RRI model is a two dimensional model capable of representing rainfall-runoff and flood inundation at once (Sayama et al. 2012).

The main function of RRI was to provide water flow and level information in emergency situations e.g. it simulated the extent and depth of floods in Pakistan and Thailand. At a given grid cell and time stage, the rainfall-runoff relation and inundation are quantified (Sayama et al. 2012).

In flood dominated catchments where subsurface flow becomes critical 2-D diffusive wave equations are employed for better representation of soil-water interaction. Integrated mathematical equations used in the RRI model are based on the Runge-Kutta method which facilitates large and complex basins to be simulated in less time with reasonable accuracy. Flows in the river channels are quantifies by 1-D diffusive wave model. Different overflowing formulae are employed, owing to the height of river bank and the level of water flows, to estimate the water interaction between slope and river channel cells. Geographic information like elevation details, land-use and runoff data being the input, simulations with RRI model can provide the water level over the slope (m), its depth in the channel (m), discharge (m^3/s) at each grid cell.

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CHAPTER 4: CLIMATE CHANGE IMPACT ON STREAMFLOWS OF ASTORE RIVER BASIN

4.1 BACKGROUND

This study selects the Astore River basin, one of the sub-basins of the upper Indus basin (Figure 4). For hydrological modeling snow and glacier melt models have been used with the RRI model. The modeling requires less parameters to simulate the river flows unlike the energy balance method which is data-extensive. This study separately calibrates the snow melt model with observed snow water equivalent before hydrologic simulations. The modelling approach is simple and can accommodate various data patterns and climate scenarios. The objectives of the study are to check the suitability of observed climate data for hydrologic modeling, use the RRI model with snow and glacier melt models and quantify the effects of climate change on the river flows. This study will help in understanding the basin's water cycle and to make this knowledge relevant to local actors and decision makers for adaptation planning. This research will be useful in estimating the impacts of climate change and extremes on water availability, hydropower generation and water related hazards.

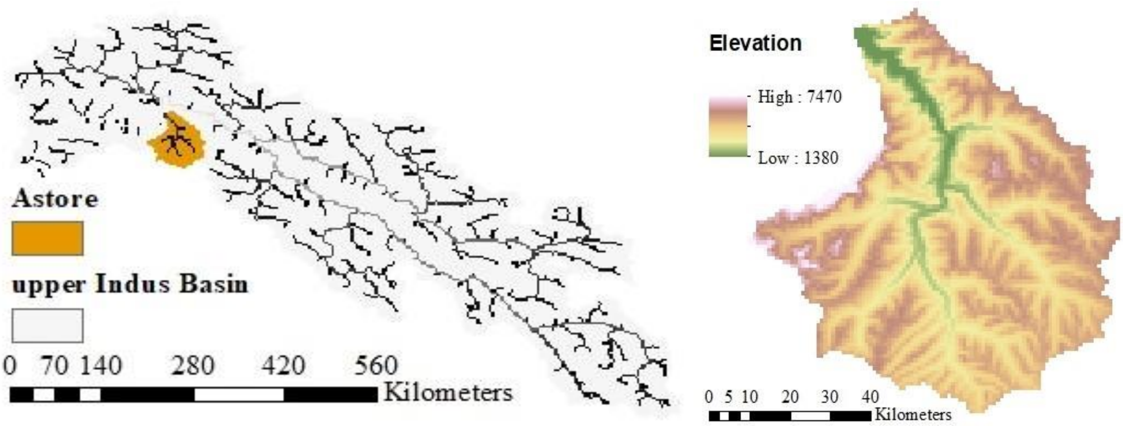

Figure 4: Astore river basin in UIB and its elevation details.

4.2 STUDY AREA

The Astore river basin flows from Himalayan mountain range. The elevation ranges between 1380 and 7470 m (Figure 4). The basin covers area of 3927 km^2. Most of the area (~87%) lies between elevation ranges of 3000-5000 m.

There are four climate stations in the basin, their elevation and time period are given in Table 7. Average annual precipitation at all the stations shows a positive trend with elevation. The highest elevation of any climate station is 4208 m above sea level that means the climate situation at above elevations is unknown. The average annual precipitation at four stations is around 650 mm annually (2002-08) which is significantly less than specific discharge (1136 mm) during the same period.

Table 7: Elevation and average precipitation of the climate stations in the Astore river basin.

Station	Elevation(m)	Average Precipitation (mm)	Time period
Astore	2168	487	2001-08
Rama	2667	650	2001-08
Rattu	3220	675	2001-08
Burzil	4208	782	2001-08

Figure 5 shows monthly maximum and minimum temperatures in the basin, the trend in the temperature decrease with elevation is evident. At Burzil the maximum temperature remains above freezing from April to October. Astore and Rattu which are located at lower elevations show above freezing temperatures throughout the year.

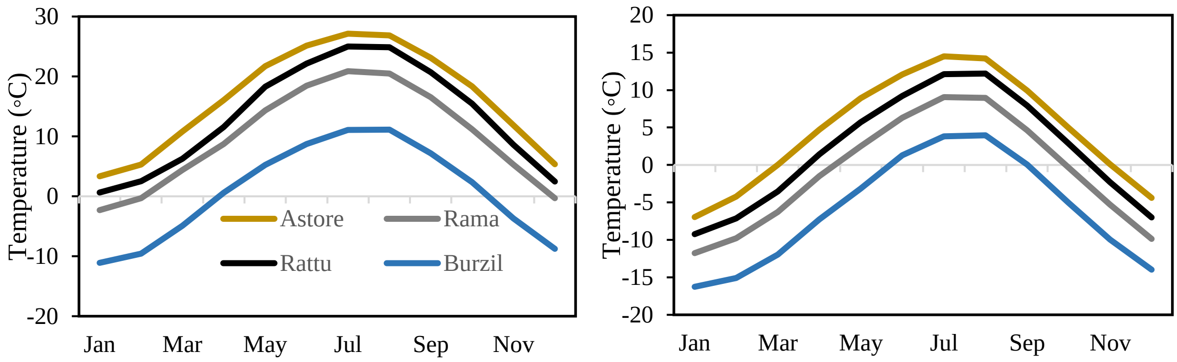

Figure 5: Monthly maximum and minimum temperature at the climate stations in the Astore basin

Monthly precipitation at the four stations is shown in Figure 6. The winter dominated precipitation is showed by the graph. Precipitation from October to April falls as snow and starts to melt in the May. The lower precipitation in the summer season (May to September) adds up to the snow and glacier melt to give maximum flows during these months.

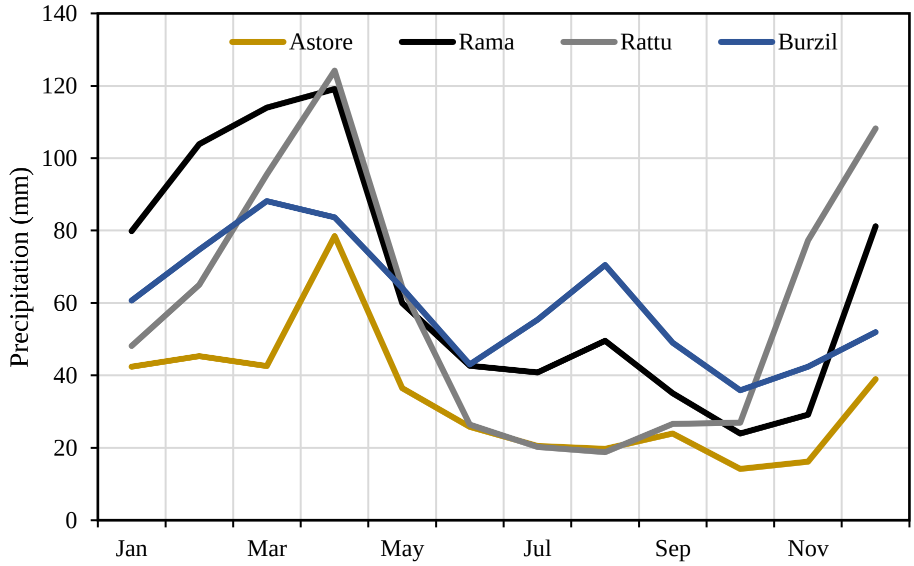

Figure 6: Mean monthly precipitation at the climate stations

MODIS snow cover product (Hall and Riggs, 2001) for 2008 has been used to explain the spatiotemporal pattern of snow cover in the basin. The snow cover is 97% of the total area in January. The melt starts from low elevation zones and progresses to higher zones from April to July. In the April 82% of basin was snow covered which reduced to 65% in May, 34% in June and 15% in July. The winter starts in September with snow fall at high altitudes. In September the snow cover increases to 43% as shown in Figure 7. The snowfall continues in the winter and cover reaches ~97% in December. Glacier cover is 316 km^2 which constitutes 8% of the basin area (ICIMOD, 2011). Glaciers are present above 3000 m while 68% of glaciers are present between the elevation range of 4000 to 5000 m.

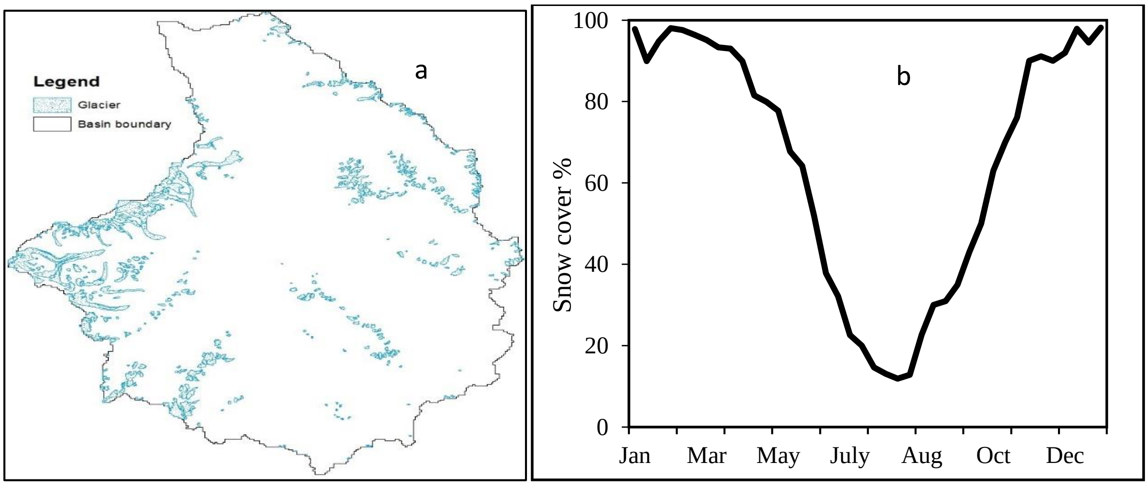

Figure 7: a) Glacier cover b) snow cover in the Astore river basin

Annual hydrograph is melt-dependent i.e. increases with the snow and glacier melt in summer (May to September). In summer it raises to 310 m^3/s on average while during winters the streamflow remain around 45 m^3/s (Figure 8). Rainfall contributes in the monsoon season (July~ September) however it less in quantity which can be understood by precipitation trends in Figure 6.

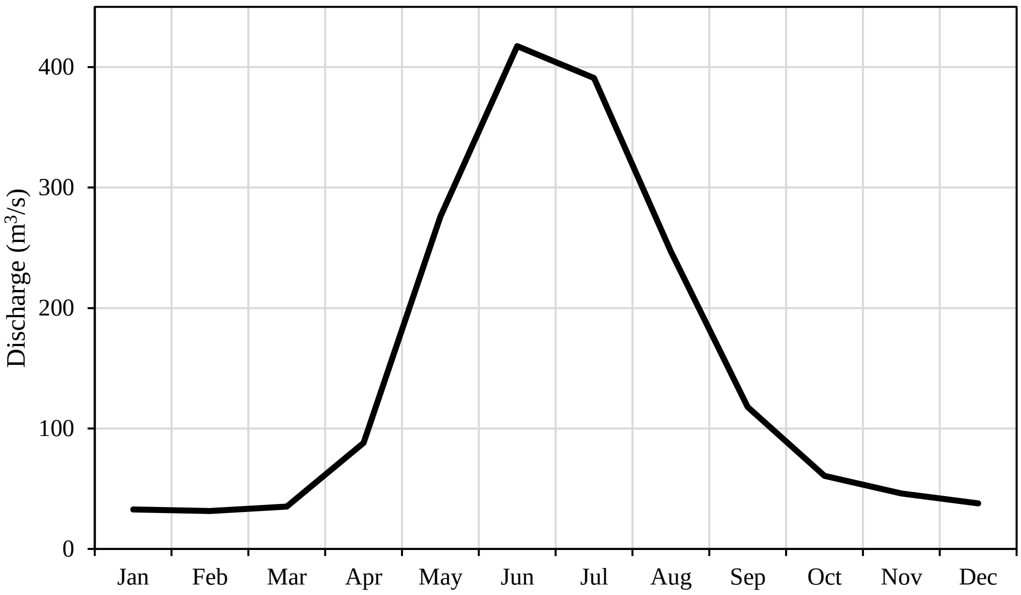

Figure 8: Average monthly river flows in the Astore river basin

4.3 METHODOLOGY

4.3.1 CLIMATE SCENARIOS

The potential impacts of climate change on the discharge of the Astore river are of great concern because runoff is melt-water dependent. Hence, it is necessary to completely understand the role of climate conditions in melting process. Many climate modelling studies have published future climate's projections under IPCC's emission scenarios. With global warming, future rainfall and temperature are likely to change in different spatial-temporal patterns. Wester et al. (2019) in their assessment of future climate of Karakoram-Hindukush-Himalaya mountains presented climate projections from CORDEX and CMIP5 experiments. Both experiments concur on significant changes in temperature and precipitation albeit different in magnitude. Temperature increase is more critical in terms of glacier mass balance. Apart from climate scenarios glacier coverage scenarios given by Huss and Hock (2015) have been employed for simulations in this study.

In this study eight scenarios of varying temperature and precipitation have been selected for simulations from Wester et al. (2019). Coupled Model Intercomparison Project 5 (CMIP5) and

Coordinated Regional Downscaling Experiment (CORDEX) have projected the future climate of the region as a results of general circulation model simulations. Projections under two RCP scenarios 4.5 and 8.5 of 24 climate models have been used to project the future climate (Table 8 and Table 9).

Table 8: Future temperature projections (°C) used for the Astore river basin (Wester et al. 2019). The values in the brackets show ranges.

Scenario	**Period**	**Ensemble**	**Summer**	**Winter**
RCP 4.5	2036-65	Cordex RCM	2.0 (1.2, 3.3)	2.3 (1.4, 3.2)
		CMIP5	2.6 (1.7, 3.3)	2.1 (1.2, 3.2)
	2066-95	Cordex RCM	2.6 (1.4, 3.7)	3.1 (2.2, 4.1)
		CMIP5	3.3 (2.5, 4.1)	3.0 (2.1, 3.4)
RCP 8.5	2036-65	Cordex RCM	2.7 (1.7, 4.3)	3.2 (1.8, 4.4)
		CMIP5	3.3 (2.5, 4.3)	3.0 (2.2, 3.9)
	2066-95	Cordex RCM	4.9 (3.0, 7.7)	5.4 (3.9, 8.2)
		CMIP5	5.7 (4.0, 7.1)	5.1 (3.8, 6.3)

Table 9: Future projections of precipitation (%) used for the Astore river basin (Wester et al. 2019). The values in the brackets show ranges.

Scenario	**Period**	**Ensemble**	**Summer**	**Winter**
RCP 4.5	2036-65	Cordex RCM	−0.1 (−11.6, 19.7)	7.0 (−13.9, 21.9)
		CMIP5	0.8 (−17.1, 35.1)	1.0 (−10.2, 18.0)
	2066-95	Cordex RCM	3.5	14.1

			(−9.8, 29.3)	(−4.9, 34.4)
		CMIP5	−0.3 (−23.2, 34.8)	6.2 (−6.8, 43.3)
RCP 8.5	2036-65	Cordex RCM	3.7 (−13.8, 22.3)	12.8 (−12.3, 28.8)
		CMIP5	3.6 (−16.6, 48.8)	5.1 (−10.9, 36.0)
	2066-95	Cordex RCM	3.9 (−14.9, 60.0)	12.9 (−30.3, 35.4)
		CMIP5	5.0 (−17.7, 79.9)	6.9 (−20.9, 54.7)

Huss and Hock (2015) used a glacier model to estimate the impact of global glacier change on sea-level rise. The ERA-Interim reanalysis data is employed table shows the reduction in the area of glacier area in future. The future change in the glacier cover has been quantified based upon two RCP scenarios throughout the late century 2100. By 2050 the glacier will lose one-third of the area and more significant reduction is expected in the late century where almost there-fourth of area will vanish. Table 10 shows the change in the glacier area in the Himalaya-Karakoram region under RCP 4.5 and 8.5 in the later part of century.

Table 10: Retreat of glacier in the basin in future (Huss & Hock, 2015)

Scenario	**Mid century**	**Late century**
RCP 4.5	35%	60%
RCP 8.5	40%	70%

The glacier cover will shrink as a result of climate warming, the change in the area is given in Table 11. The reduction in the area will initiate from the lower elevations. The distribution of glacier area with in different elevation zones.

Table 11: Present and future elevation-area distribution of glacier in the basin

Elevation bands (m)	**Glacier area distribution (km^2)**	**RCP 4.5 mid century**	**RCP 4.5 end century**	**RCP 8.5 mid century**	**RCP 8.5 end century**
3000-3500	4	0	0	0	0
3500-4000	18.5	0	0	0	0
4000-4500	41.8	0	0	0	0
4500-5000	172.2	126.5	110.1	47	15.3
5000-5500	42.3	42.3	42.3	0	42.3
5500-6000	23.4	23.4	23.4	0	23.4
6000-7000	10.4	10.4	10.4	0	10.4
Above 7000	3.4	3.4	3.4	0	3.4

4.4 RESULTS

Figure 9 shows the total monthly precipitation in the basin at 3000 m. The precipitation extrapolation rate of 0. 03 %/m is applied to calculate the precipitation time series for other zones. Immerzeel et al. (2015) reports the precipitation extrapolation rate of 0.044% in the Hunza river basin which is located in the adjacent north of Astore river basin. This assumption of a monotonous precipitation rate overestimates the snowfall above 5000 m. However, this doesn't affect the overall simulation results because merely 3.5% of basin area lies above 5000 m and contribute little in the hydrologic cycle.

Since most of the precipitation falls as snow in winter as evident from Figure 7. The contribution of runoff throughout elevation zones is highly variable. The precipitation does increase with elevation but the presence of glaciers between 3000 and 5500 m bring additional runoff from these zones. The zones above 5500 m receive most precipitation as snow and remain below freezing or just above, thus contribute less to runoff.

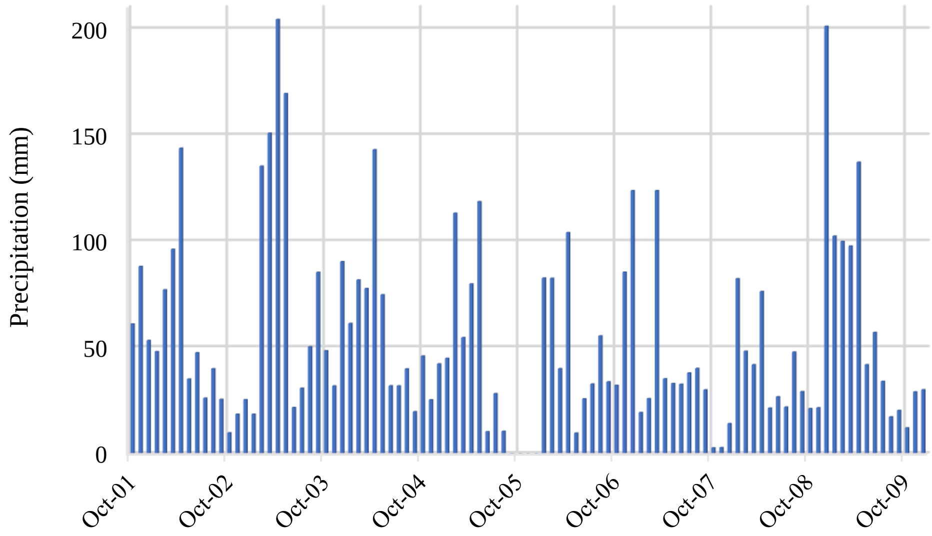

Figure 9: Average monthly precipitation in the basin

Snow melt's accuracy is important for assessment of water balance in the basin. The snow melt model is calibrated with observed snow water equivalent (SWE) recorded at Deosai station, located 60km outside the basin at 4010 m.a.s.l. Precipitation and temperature time series of the station were provided by WAPDA. SWE values have been digitized from Hasson et al. (2014). Time span from November 2007 to June 2010 is selected to calibrate the Cema-Neige model. The threshold temperature to separate snow and rainfall is 0◦C and the degree day factor during the melt season was 6 mm/◦C. In total 61% of precipitation was snow which starts to accumulate in November and reaches maximum in March (Figure 10). The melt season starts in May and continues till June. The model has been able to simulate the accumulation and melt of seasonal snow at point location.

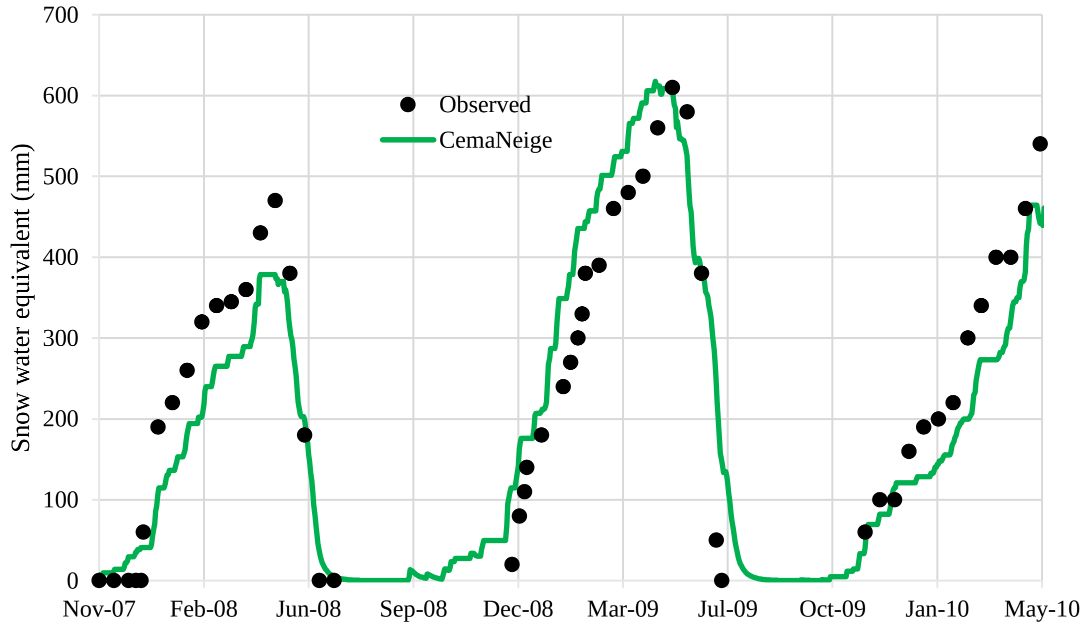

Figure 10: Calibration of snow water equivalent

The simulation was performed for 7 years, Jan 2002~Dec 2005 for calibration and Jan 2007~Dec 2008 for validation. The simulated discharge with observed and runoff is shown in Figure 11. Model has simulated the response of catchment well with representing the peaks satisfactorily. The model assumes that the precipitation and temperature remain constant throughout the given elevation zone which has resulted in inconsistencies in the simulations. More detailed approximation of climate parameters at finer scale and accurate distribution of glacier melt will produce better simulation in space and time. Like precipitation glacier melt is assumed to be constant for any given zone which should be made more accurate by considering grid-based melt computation.

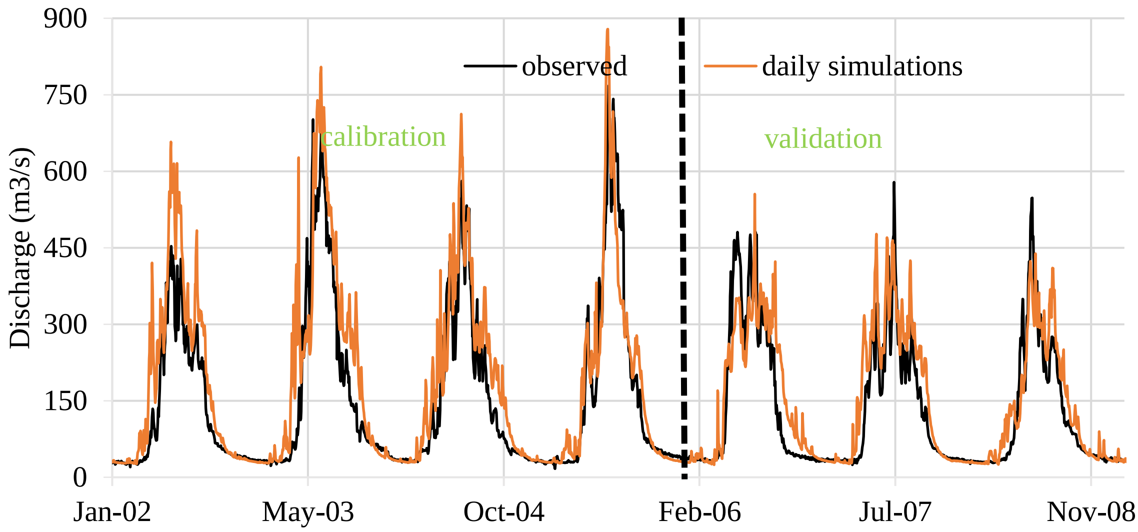

Figure 11: Simulation results of river flows of Astore river

Annual contribution of rainfall, snowmelt and glacier melt is shown in the Table 12. Second column shows the contribution of rainfall. Third column shows snow melt and fourth column shows the glacier contribution. The contribution of melt water in the streamflow is 65% ~73% annually.

Table 12: Runoff components, simulated and observed runoff and model performance

Year	Rain (mm)	Snow (mm)	Glacier (mm)	Simulated runoff (mm)	Observed Runoff (mm)	Δ	NS
2002	231	581	397	1208	1015	193	0.8
2003	334	673	412	1455	1371	84	0.82
2004	278	548	377	1197	1180	17	0.86
2005	190	612	414	1442	1350	92	0.75
2006	171	385	477	1192	1140	52	0.68
2007	144	424	457	1313	1050	273	0.74
2008	149	251	459	1089	964	125	0.74

Altogether melt water contribution is higher than rainfall owing to the presence of glaciers and heavy winter snowfall. Separate hydrographs describing the runoff components is shown in

Figure 12. Rainfall is higher in early spring and in monsoon season though suppressed as compared to the earlier. This trend in the rainfall hydrograph can be ascertained from the hyetograph where monsoon precipitation is lesser. The snowfall is the major source of hydrograph contributing 40% annually. Glaciers which starts contributing in July and continues for three months. During July, August and September the overall contribution of glaciers is higher than snowmelt and rainfall combined. Overall their share is 32% in annual hydrograph.

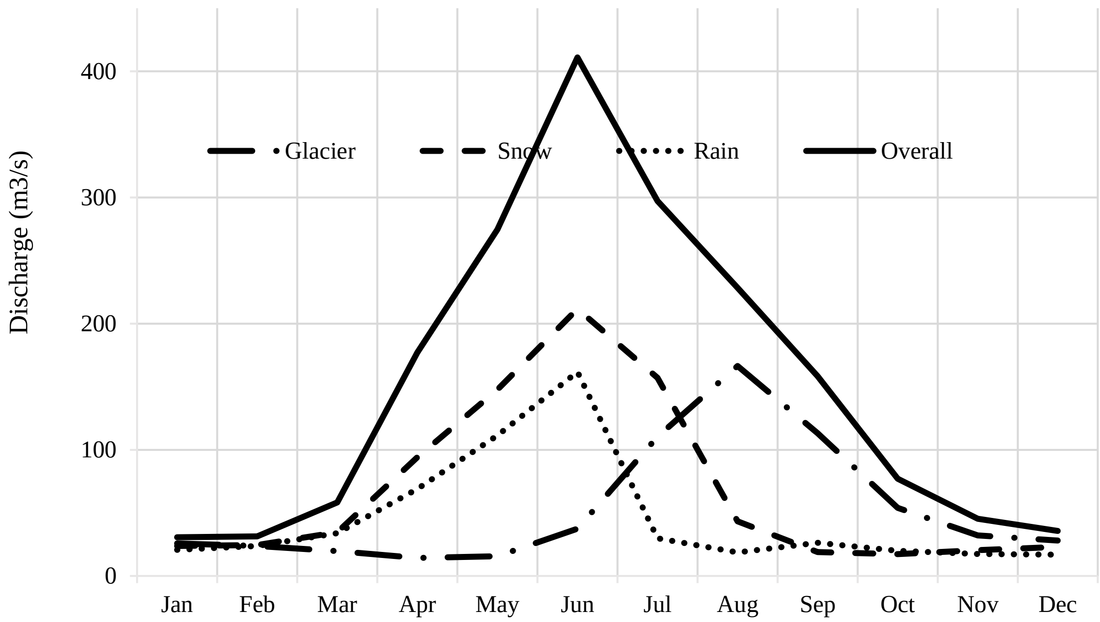

Figure 12: Contribution of rainfall, snow and glacier melt in the river flows

The future river flows are shown in Figure 14 and Figure 15. All future scenarios project higher spring flows mainly due to the higher winter precipitation. By md-century, the summer flows will increase approximately 11% because higher temperatures will melt more glaciers. In principle till the mid-century no substantial change is expected in the average annual flows under both RCPs 4.5 and 8.5. However, in the late century considerable reduction is projected as shown in Figure 13 and Figure 14.

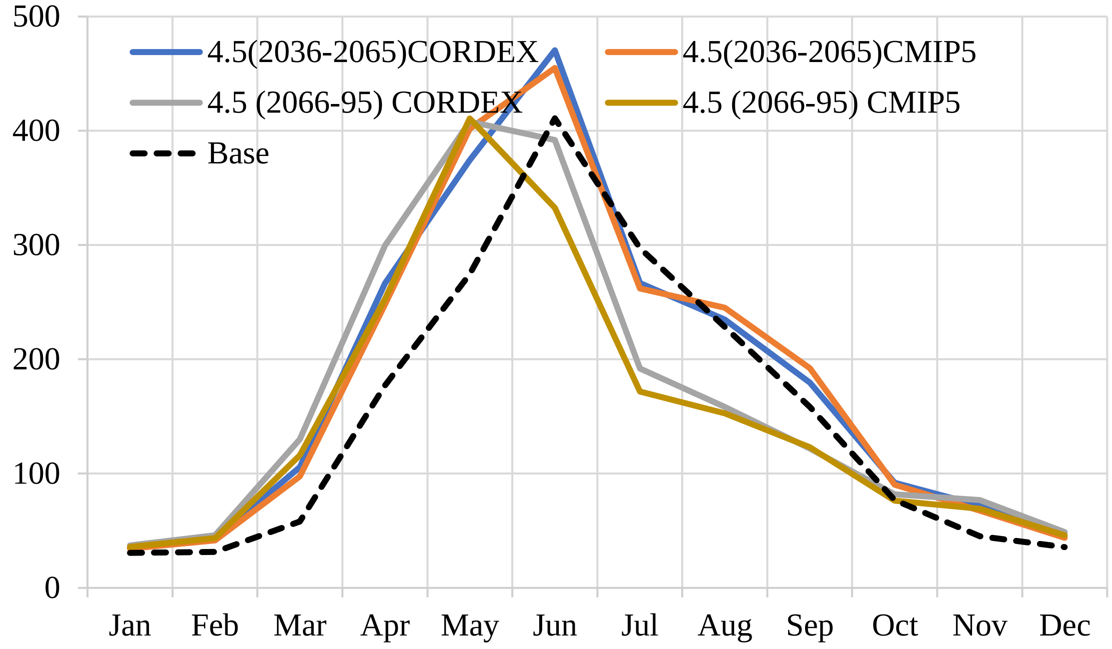

Figure 13: Change in mid and late century river flows under RCP 4.5

In late century RCPs 4.5 and 8.5 will see considerable decrease in the contribution mainly due to glacier retreat. The projected increase in the summer precipitation during this time would help little to sustain the flows at the present level. Spring flows will continue to be higher under both RCPs than current flows, in summer the flows will experience sharp decline and up to half of the flows will disappear. In spring the opportunities to generate hydropower and irrigation will increase. However, summer season will witness greater stress on available water resources.

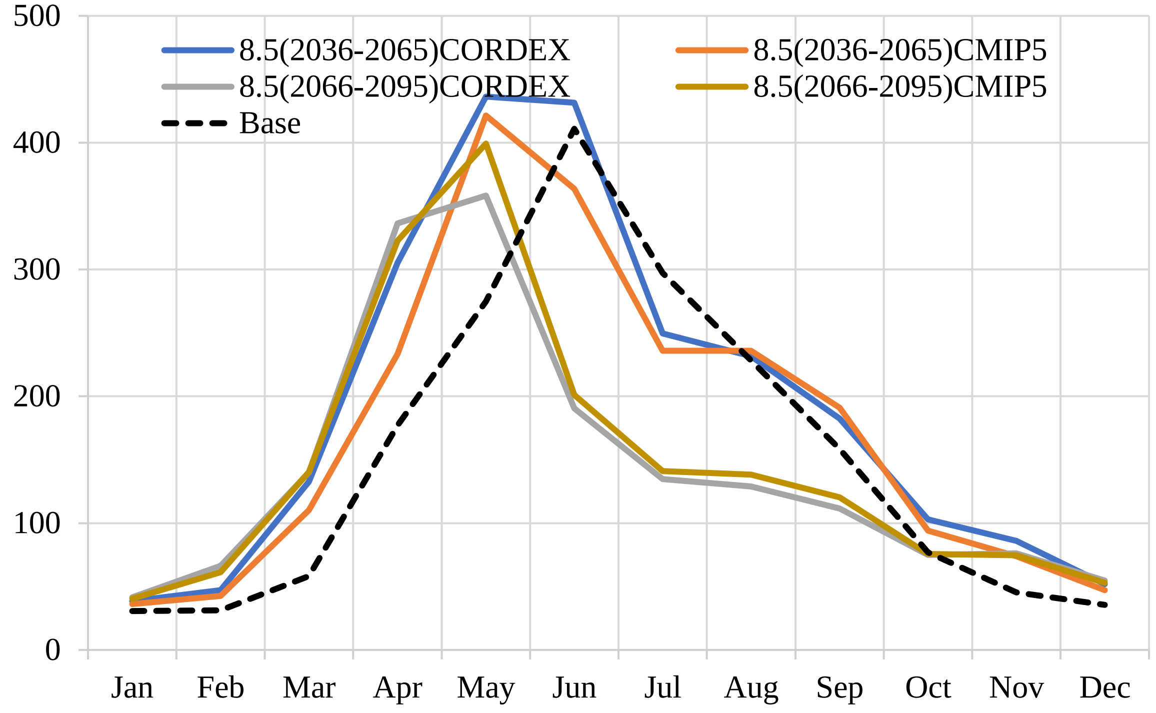

Figure 14: Change in mid and late century river flows under RCP 8.5

4.5 CONCLUSIONS

The melt model and RRI have been able to simulate the response of the basin well. The climate conditions at higher elevations i.e. 3000 m ~ 5500 m play the most vital role in the runoff generation. However, betterment in the estimation of precipitation and temperatures is required on spatial scale. The model can be used to evaluate the impacts of receding glacier cover and changing climate on water balance etc.

Winter precipitation is projected to increase which will cause increased spring river flows. This will provide increased potential for irrigation and hydropower during spring. However, probability of localized flooding will increase. On the other hand, the extra water in the months of spring should be stored to meet the demands of the following months which will have lower river flows.

Higher temperatures will extend glacier melt seasons and enhance glacier melt rates. This impact is temporary, however, and glacier mass will eventually be sufficiently reduced to restrict total meltwater contribution.

Glacier reduction in the late century will play vital role in the reduction if summer flows. Although the summer precipitation is projected to increase but it will not be enough to sustain the present quantity. 60 to 70% loss in the glacier area will reduce the summer flows up to half in July and August.

Overall futuristic strategies in terms of environmental conservation and economic development will ensure adaptation to changes in water supply.

4.6 REFERENCES

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CHAPTER 5: IMPACT OF CLIMATE CHANGE ON RIVER FLOWS IN THE UIB AND ITS SUBBASINS

5.1 CLIMATE AND HYDROLOGIC DATASETS

This chapter discusses the suitability of global climate datasets for the hydrologic modeling in the UIB. Furthermore, future climate impacts are also shown on the river flows of UIB and sub-basins. The distribution of elevation in the UIB and hypsometric curve are shown in Figure 15. The basin has a maximum elevation of 7,528 m. The total area of the basin is 192,861 km^2. About two-thirds of the total area lies between the elevations of 3,500 and 5,500 m. In general, the eastern sub-basins have higher altitudes than the western sub-basins. The study area also consists of three sub-basins: Gilgit, Shigar and Kharmong.

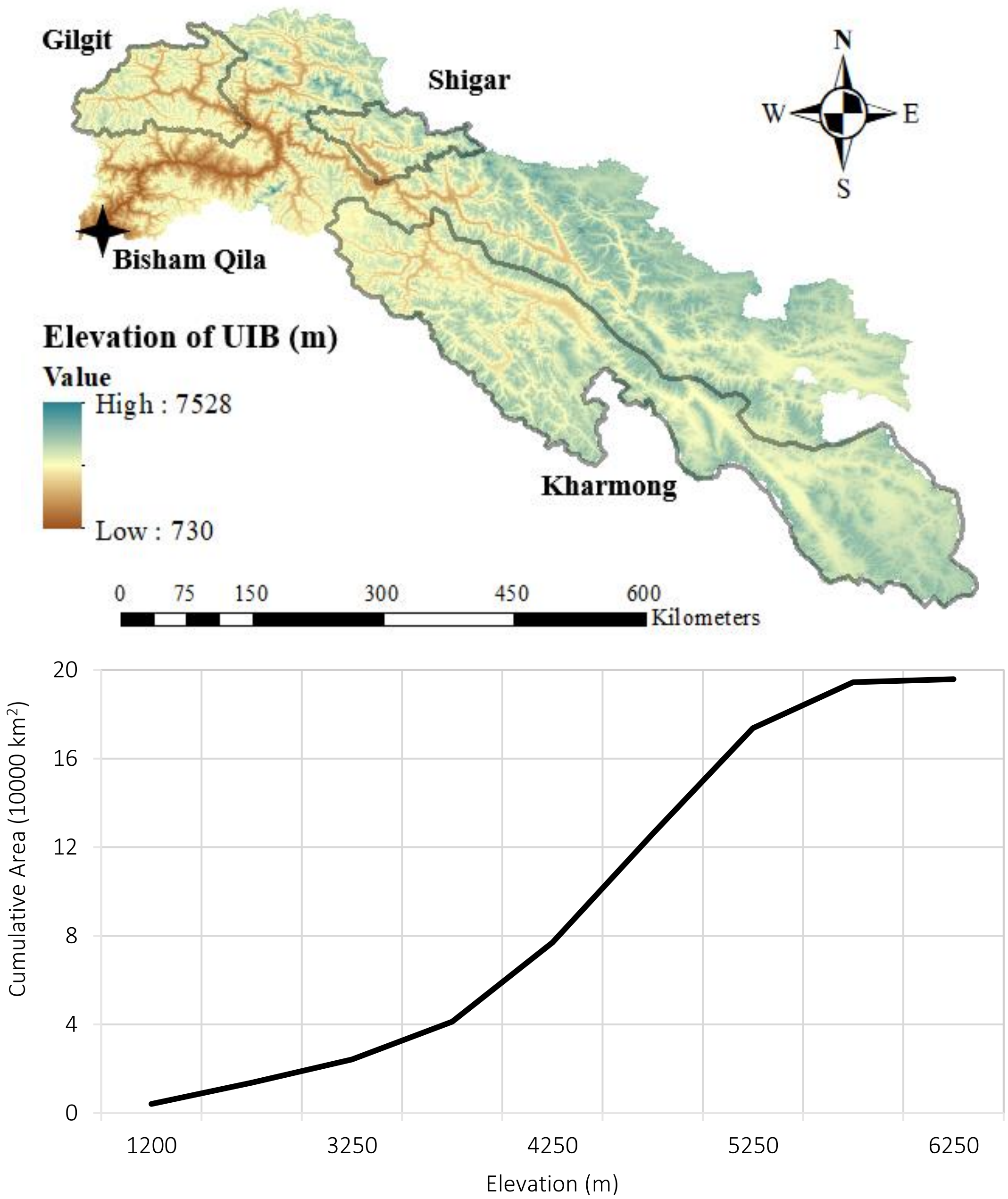

Figure 15: UIB, three sub-basins and its area-elevation distribution

The glacier cover is extracted from the dataset prepared by ICIMOD (2011), which contains detailed information related to clean and debris covered glaciers. Figure 16 shows glacier in the basin and distribution of clean and debris-covered glaciers. The total glacier area in the basin is 7,912 km^2 which is 4.1%. Among them, the clean ice covers the area of 7,156 km^2 and ice with debris covers is 756 km^2. The north-west hosts most of the glacier mass, the sub-basins in that region i.e. Hunza, Gilgit and Shigar have higher glacier weightage in runoff as compared to snow melt and rainfall (Mukhopadhyay & Khan, 2015).

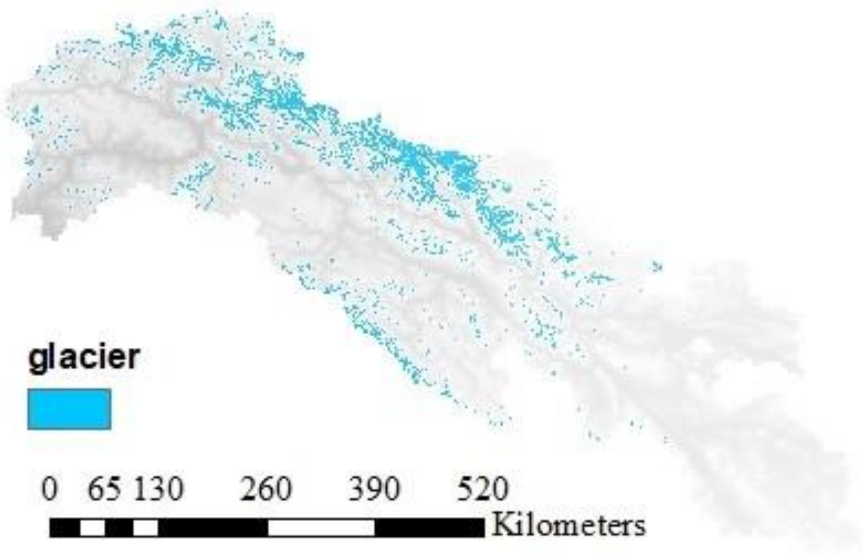

Figure 16: Glacier cover estimated by Landsat in the UIB in 2005

Table 13: Area, elevation and glacier cover of UIB and sub-basins.

Basin	Area (km^2)	Elevation (min, mean, max) (m)	Glacier (%)
UIB	192,861	733, 4600, 7528	7.4
Gilgit	13,100	1468, 4030, 6162	13.0
Shigar	6,900	2189, 4520, 7360	28.8
Kharmong	70,000	2409, 4790, 6470	3.6

The observed monthly discharge (1980–2007) at the Bisham Qila is shown in Figure 17. Even in winter (October–April) with limited rainfall, the average monthly flow is sustained at approximately 450 m^3/s. This base flow is mainly due to the snow and glacier melt, as explained by Mukhopadhyay and Khan (2015). The flow regime between May and September is important because of its considerable contribution to meet the water demands of the entire Indus River basin.

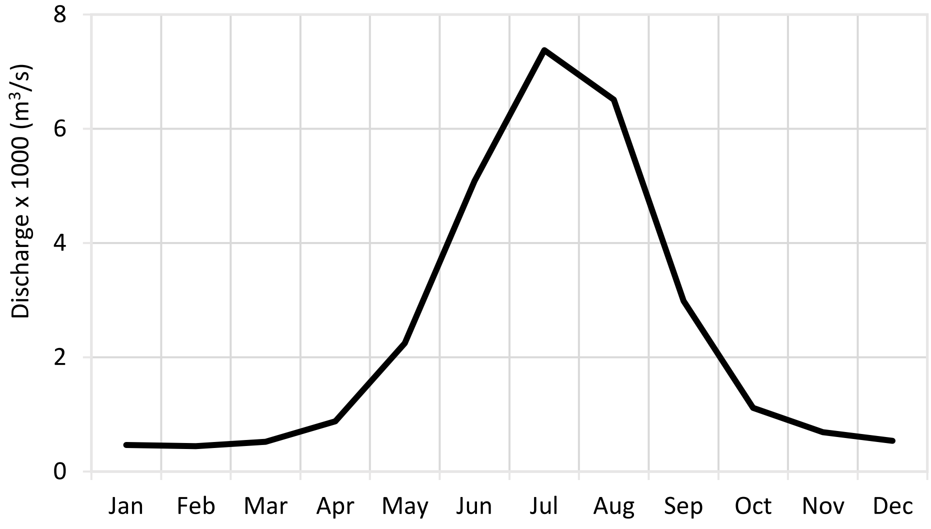

Figure 17: Observed average monthly river flows at Bisham Qila (1980-2005)

Figure 18 shows the frequency distribution of the daily river flow at Bisham Qila. The daily discharge corresponding to the non-exceedance probability or 99% (Q99) was 12,452 m^3/s, and Q75, Q50, and Q25 are 10,380 m^3/s, 6,915 m^3/s, and 3,463 m^3/s, respectively.

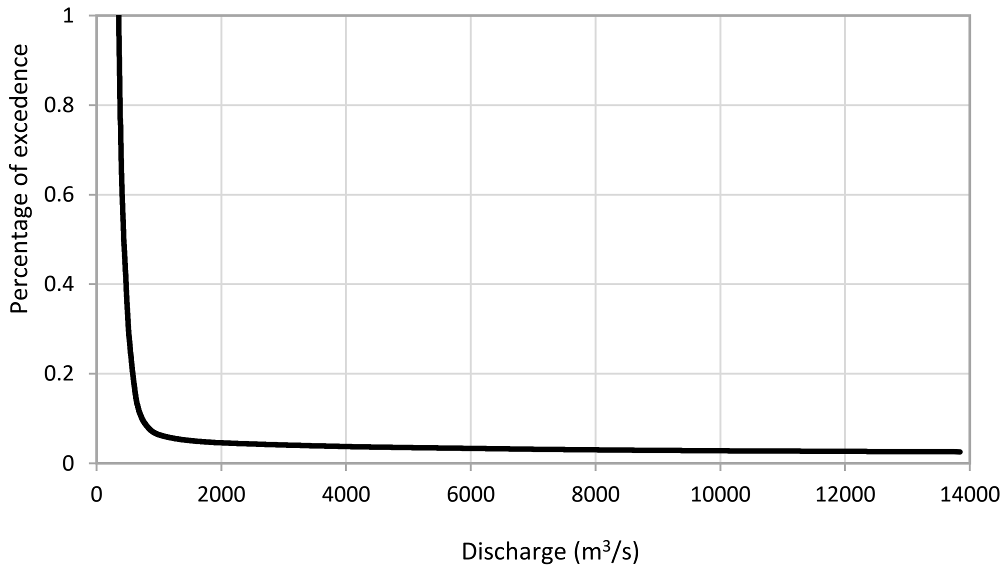

Figure 18: Exceedance probability of river discharge at Bisham Qila (1980-2005)

For hydrological modeling of river flows the Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE) (Yatagai et al., 2012) climate dataset was used along with glacier cover (ICIMOD, 2011) of the region. Figure 19 shows seasonal precipitation and temperature variation in the basin. The original Aphrodite dataset of precipitation was corrected using the method introduced by Immerzeel et al. (2015) and explained in section 2.1. Winter precipitation consisting of November and April are higher than summer (May to October). Higher elevation zones receive heavy precipitation in winter in the form of snowfall. The eastern edge of the UIB is shown to have a high rate of precipitation in summer because it coincides with the western Himalayas, where the monsoon season is very dominant.

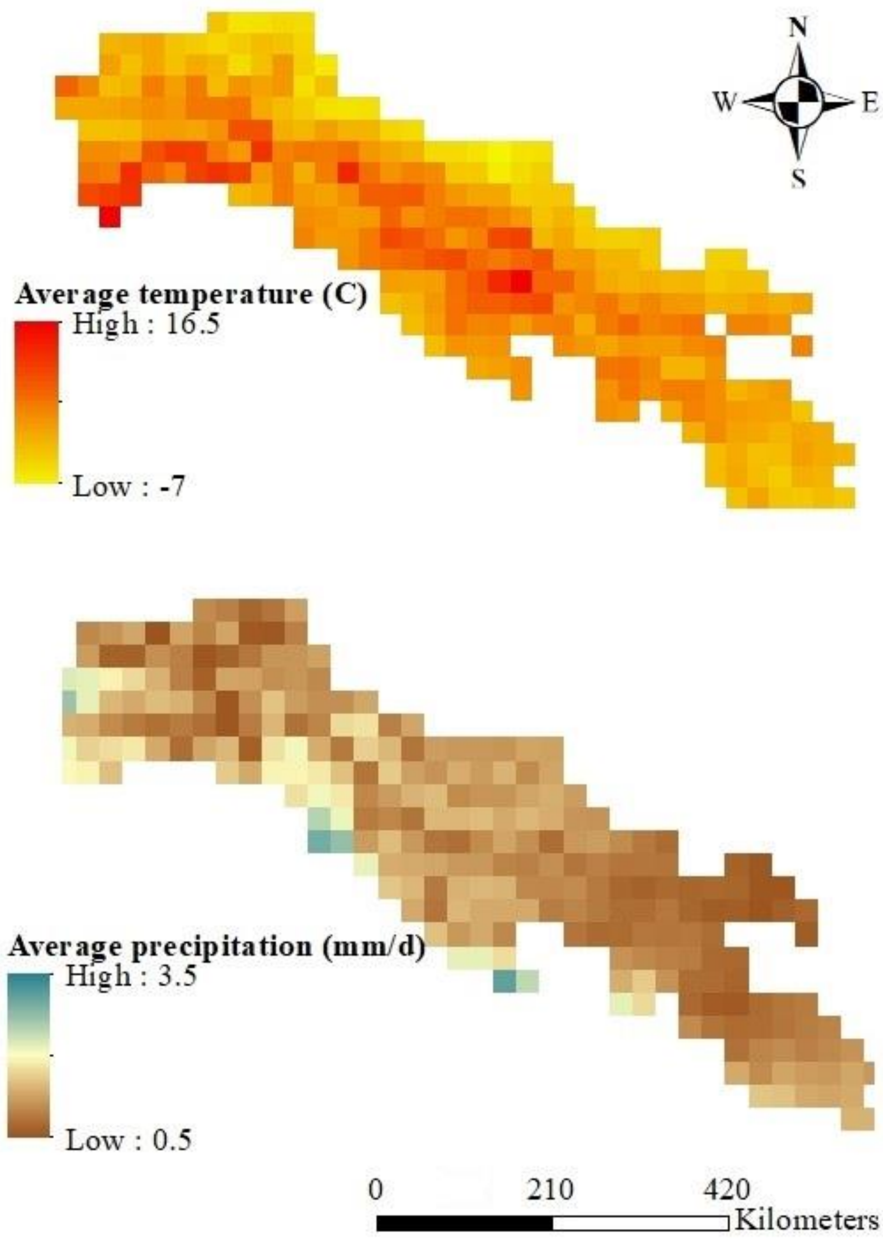

Figure 19: Distributions of (a) average temperature and (b) precipitation in the UIB according to APHRODITE in (1980-2005).

On an annual basis, the southern edges and eastern region of the UIB receives higher precipitation. Winter receives heavy rainfall due to western disturbances, and the monsoon causes the precipitation in July and August.

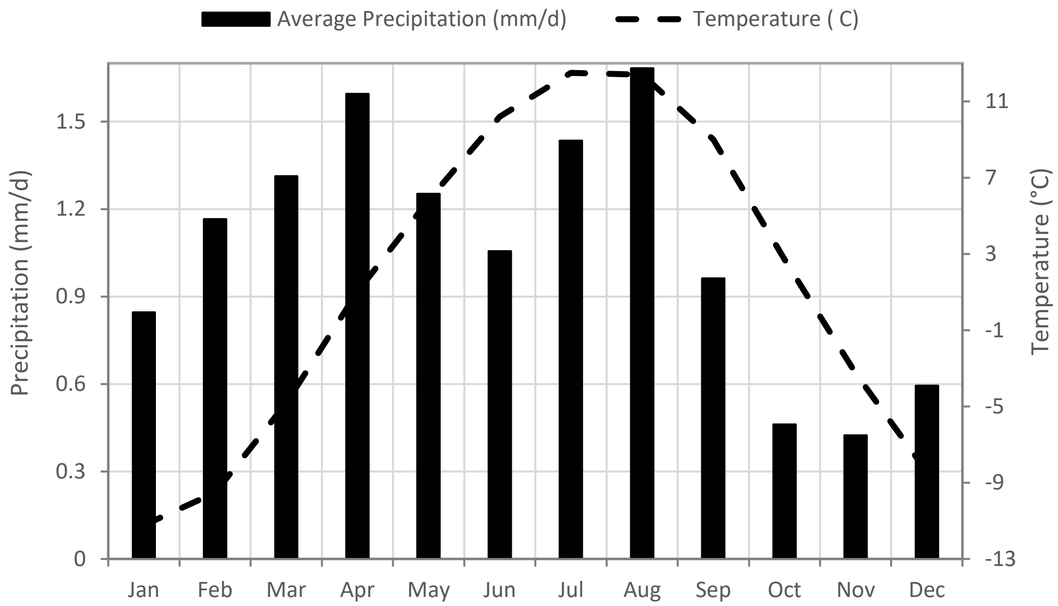

Figure 20: Basin average temperature and precipitation in the UIB (1980-2005)

Temperature remains lower in the northern and eastern regions of the UIB, while the lower elevation zones in the western region are warmer (Figure 19). Over the higher elevation zones average temperature remains ~0 ◦C and maximum temperature remains around 23 ◦C. The annual average temperature remains between 12 and to -8 °C (Figure 20).

5.2 RESULTS AND DISCUSSIONS

5.2.1 MODEL CALIBRATION AND VALIDATIONS

The simulated discharge at Bisham Qila is shown in the Figure 21. Simulation period consists of twenty-six years from 1980 to 2005. The simulation is divided into two periods of calibration and validation. Calibration consists of 13 years from 1980-1992 while validation comprised of remaining period. Simulated river flows are calibrated and validated with observed river flows at Bisham Qila and the performance is checked using several statistical parameters. Nash-

Sutcliffe coefficient (NS), percent bias (PBIAS) and root mean square error (RMSE) are used to analyze the simulation results (Table 14).

Table 14: Model performance parameters for UIB and three river basins.

	Calibration			Validation		
Stations	**NS**	**PBIAS**	**RMSE**	**NS**	**PBIAS**	**RMSE**
UIB	0.60	0.35	0.58	0.54	0.32	0.61
Gilgit	0.53	0.035	0.75	0.57	0.04	0.7
Shigar	0.50	0.3	0.7	0.48	0.27	0.68
Kharmong	0.45	0.28	0.72	0.41	0.32	0.64

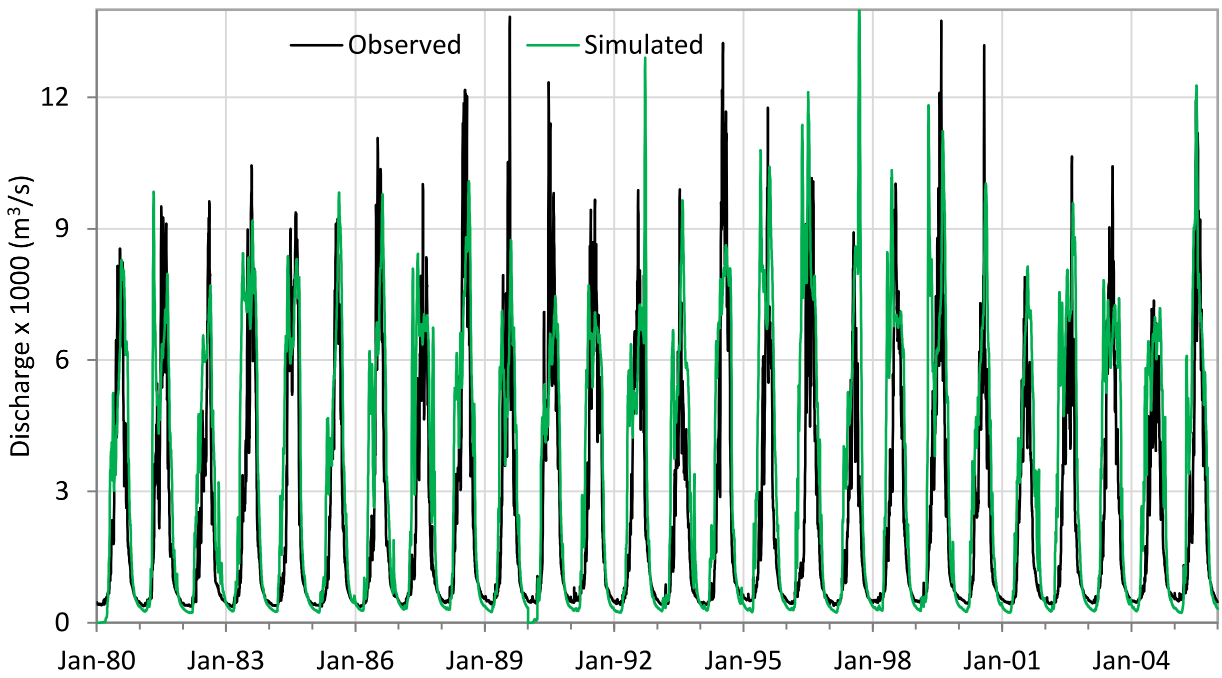

Figure 21: Simulation of river flows at Bisham Qila (1980-2005)

To explain the climatic and runoff conditions at regional level three sub-basins across the UIB, Gilgit, Shigar and Kharmong are selected. These sub-basins cover whole geographic range and differ in glacier coverage and climate. In total these three sub-basins contribute 35% of the river flows at Bisham station and of which 34% consists of glacier melt (Table 15). A common characteristic of runoff at three sub-basins and at Bisham is the higher proportion of melt-runoff versus rainfall-runoff which explains the significance of winter precipitation in the basin. Figure 22 and Figure 23 show simulations of discharge for two sub-basins of UIB, Gilgit and Shigar. They are highly glacierized and runoff is melt-water dependent.

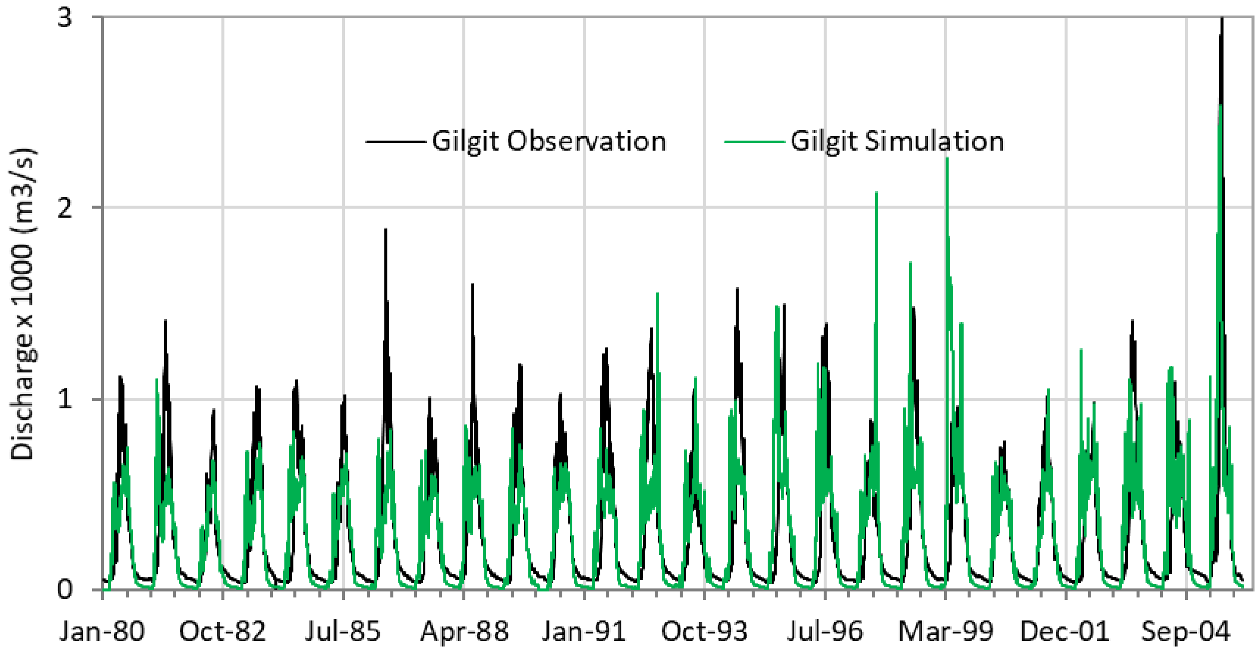

Figure 22: Simulation results at Gilgit sub-basin (1980-2005).

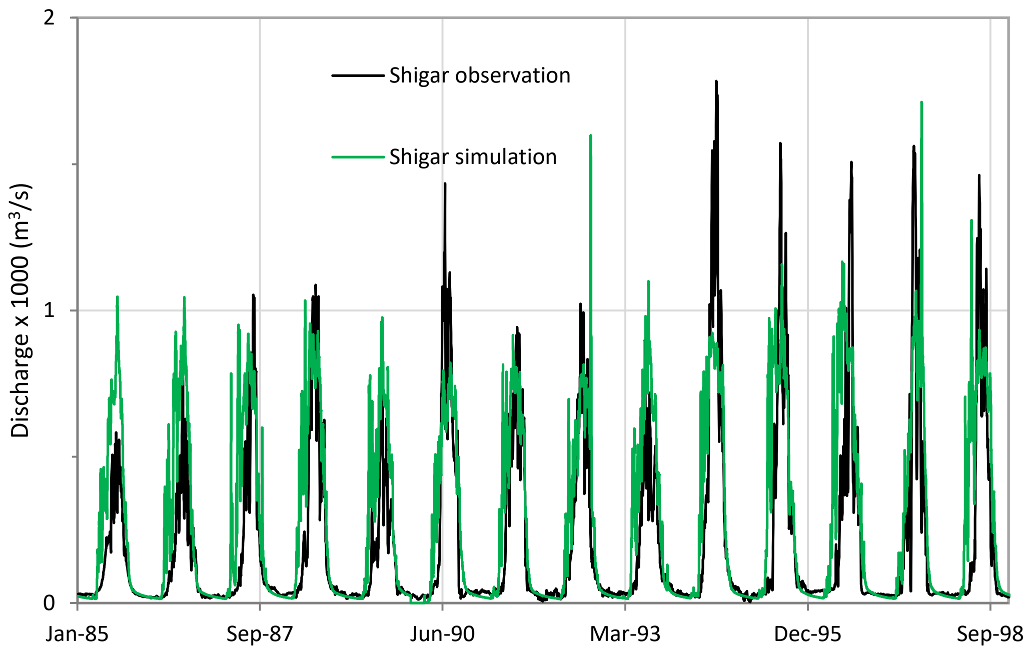

Figure 23: Simulation of river flows at Shigar river basin (1985-1998)

Gilgit is located in the western edge of UIB and has elevation range between 1472 m to 6392 m. Glacier coverage in the basin is 1684 km^2 (13.2%), almost 1181 km^2 (70%) of the glaciers are located between the elevation bands of 4000-5000 m and add significantly in the river flows. Total glacier share is 63% in annual river flows followed by rainfall with 13% share.

Shigar river basin lies in the northern region and has the area of 6900 km^2. Percentage wise this sub-basin has largest glacier coverage in the UIB. The glacier cover in the basin is 28% which contributes up to 85% in the annual river flows. It is the coldest sub-basin with average annual temperature below freezing, this cold climate has resulted in most of precipitation falling as snow.

Kharmong has large proportion of rainfall runoff as compared to glacier and snow melt because of smaller glacier cover and minimum elevation of glacier (4500 m) is higher than other sub-basins. Glacier melt has the second highest weightage in runoff components with 35% followed by snowmelt with 26% weightage (Table 15).

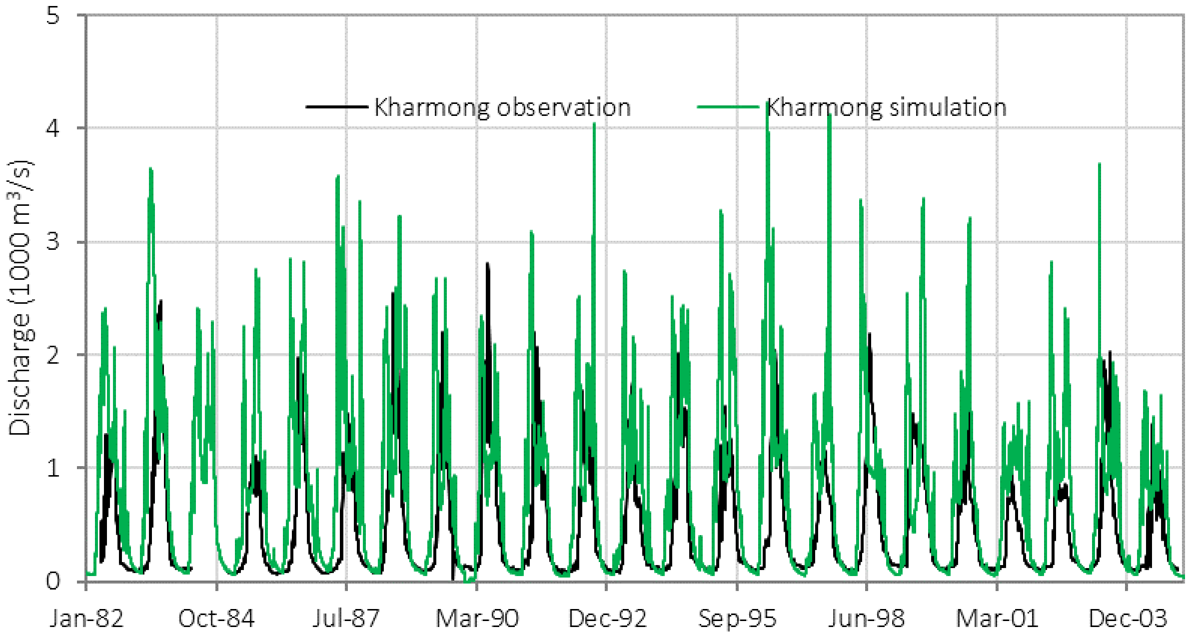

Figure 24: Simulation of river flows at Kharmong station (1982-2003).

Snow cover in the UIB is simulated using Cema-Neige model. The model uses an empirical relation to quantify the snow-covered area (Equation 13). A comparison of snow-covered areas by Cema-Neige and Moderate Resolution Imaging Spectroradiometer (MODIS) is shown in Figure 25. Figure 25 shows 5-year of snow cover plots from 2000 to 2005. Simulation of snow cover does not consider slope and aspect of the grid cell which is not the exact representation of the physical process. An important parameter of Cema-Neige model is the division of rainfall and snowfall which is based upon using 0◦C threshold. These factors are the source for disagreement with actual snow cover. Effects of wind action and avalanche contribute in the deposition of snow and can cause discrepancies in the snow cover.

The Cema-Neige simulates snow cover on daily resolution and MODIS has 8-day resolution. In the analysis of MODIS images with cloud-cover greater than 10% of the basin area have been neglected.

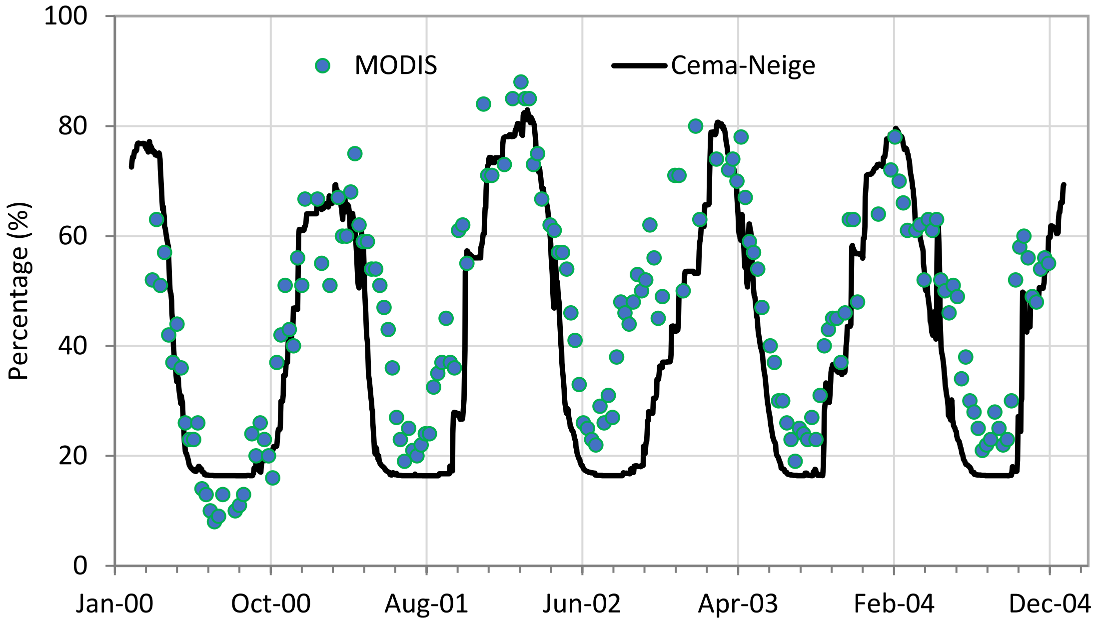

Figure 25: Comparison of MODIS snow cover with simulated snow-cover.

Overall, simulations show satisfactory results but improvements are required in the calibration of summer flows. The comparison of runoff components with other studies suggests agreements on the quantity. This agreement suggests optimization of model parameters require specific attention.

5.2.2 ESTIMATION OF SNOW AND GLACIER CONTRIBUTIONS UNDER PRESENT CLIMATE

Under current climate conditions, glacier contributes 68%, rainfall 20% and snowfall 12% in river flows (Figure 26). Runoff components have been calculated individually by running the model with the snow melt, rainfall and glacier melt obtained from melt models. Rainfall runoff is generated in the monsoon months (August and September), and the annual maximum rainfall discharge (September) is ~ 650 m^3/s. With the increasing temperature in April snow starts to melt from the lower elevation zones, and its discharge reaches ~ 1000 m^3/s (April) and ~ 2400 m^3/s. The initiation of high flows in the hydrograph is due to the snowmelt; in April (80%) and

May (73%) the river flows mainly consist of snow melt. Melt-water from higher zones, specifically glacier-melt, follows snowmelt in June. The glacier melt continues till September, dominating the hydrograph. In summer from June to September, the glacier alone contributes 85% of the total flow. In August, it reaches a maximum with an average discharge of ~5600 m^3/s.

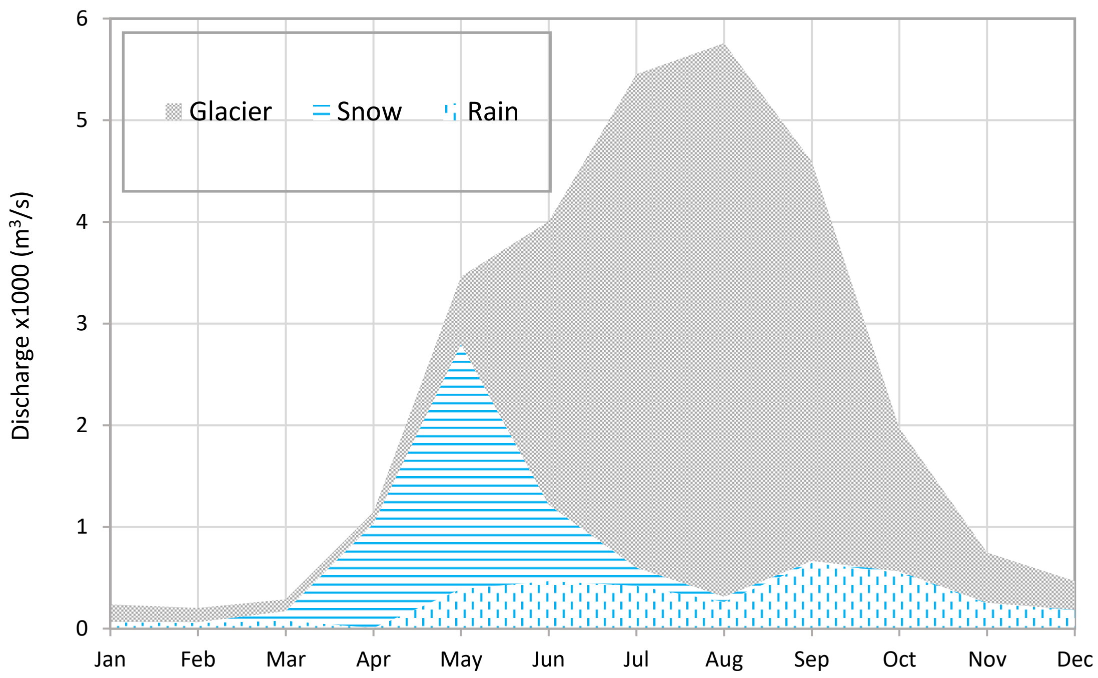

Figure 26: Monthly contribution of glacier, snow and rain at UIB (1980-2015).

The glacier-melt estimate was compared with that of other studies (e.g. Lutz et al. (2014); Mukhopadhyay and Khan (2015); Hasson et al. (2019)). Figure 26 shows the contribution of glaciers. In July, it is approximately 5200 m^3/s and in August it is approximately 5750 m^3/s. Visual analysis of graphs given in other publications show the July flows from glaciers are in the range of 4000 to 4800 m^3/s, and for August, the range is 4000 to 6100 m^3/s. Lutz et al. (2014) reported the annual glacier contribution in the UIB at Bisham Qila to be 67% which is similar to that of the simulations (Table 15).

5.3 BIAS CORRECTION OF MRI-AGCM

MRI-AGCM is a general circulation model (GCM) with a spatial resolution of 20km. The present climate is simulated using observed sea-level temperatures and it shows promising performance in the global distribution of tropical cyclones, the East-Asian monsoon etc. (Mizuta et al., 2012).

The delta-change method was selected to remove the biases in the MRI-AGCM. This method is the widely used technique that considers the mean bias is the difference between observed and GCM data (Miao et al., 2016). The future data are adjusted using this bias. The future projection can be adjusted as:

$$\tilde{x}_{m-p.adjust} = x_{m-p} + (\bar{x}_{o-c} - \bar{x}_{m-c}) \qquad (16)$$

where x is the meteorological variable of either o (observed) or m (modeled) for a historic training period or current climate (c) or future projection (p). Linear correction is another bias-correction technique that utilizes a scaling factor between observed and GCM simulations to reduce the bias in future projection.

$$\tilde{x}_{m-p.adjust} = x_{m-p} \cdot \left(\frac{\bar{x}_{o-c}}{\bar{x}_{m-c}}\right) \qquad (17)$$

The equation 16 is used to correct temperature and Equation 17 is used to adjust the precipitation.

5.4 FUTURE GLACIER AREA

The future glacier area for this study is extracted from the estimates given by (Huss & Hock, 2015). They simulated average glacier area in future using 14 GCMs for south-west Asia where UIB is located. Projected glacier area in 2099 is 6194 km^2 and in 2075 it is 9977 km^2 while present area is 32814 km^2 as shown in Figure 27. From 2010 till 2100 the western south Asia will lose glaciers at the rate of 300 km^2/year or 3.7%/year. In this study single glacier cover is considered for future (2075-2099). That singular glacier area is obtained by averaging the annual glacier areas between 2075-2099 given by Huss and Hock (2015). Current glacier area in UIB is 7,912 km^2 (ICIMOD, 2011), which according to the assumption explained in previous lines, will reduce to 2,215 km^2. Thus, from present glacier cover, glacier area is subtracted from its lowest elevations until it reached 2,215 km^2.

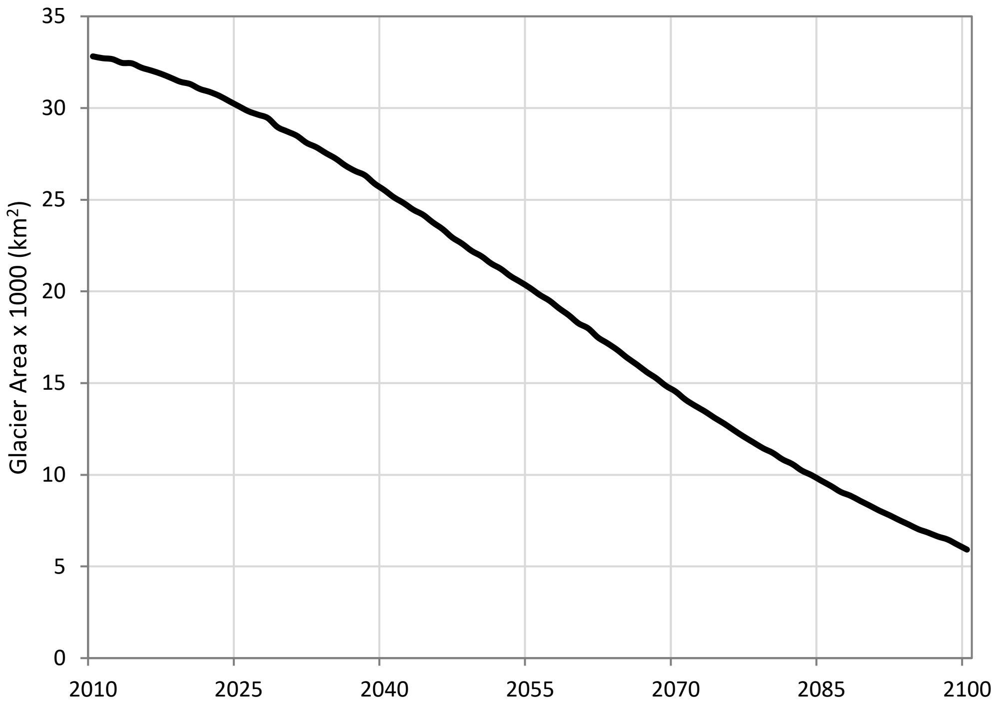

Figure 27: Average of glacier area in the UIB according to GCMs used by (Huss & Hock, 2015).

5.5 FUTURE CLIMATE IN UIB

Figure 28 shows the change in basin temperature and precipitation during 2075–2099 based on the MRI-AGCM scenarios. Across the UIB, the temperature will increase by 5.63 °C, and the largest increase of 7–8 °C is projected to occur in the September–October period. In February–March, temperature will increase in the range of 4 °C. Precipitation will increase by 17% annually. An important characteristic of the future precipitation regime is an approximately

60% increase in July–August. This trend is different from that of Lutz et al. (2016) who used CMIP5 GCMs and reported a 25% increase in the June–September period. Furthermore, Lutz et al. (2016) have shown that precipitation in the future (2071–2100) will decrease in the February–May season, while the GCM in this study projects a 20% increase in precipitation. Another study by Su et al. (2016) employs 20 GCMs from the CMIP5 annual report and shows the precipitation regime over the UIB, which is intensive during May–August. However, during September–April, precipitation either will decrease or remain within a change of 5%. Both Su et al. (2016) and Lutz et al. (2016) have used similar GCMs and projected identical precipitation regimes; however, the latter projects higher precipitation from September–December. This difference in future climate projections is probably because Su et al. (2016) projected for 2041–2070 and Lutz et al. (2016) for the subsequent 30 years (2071–2100).

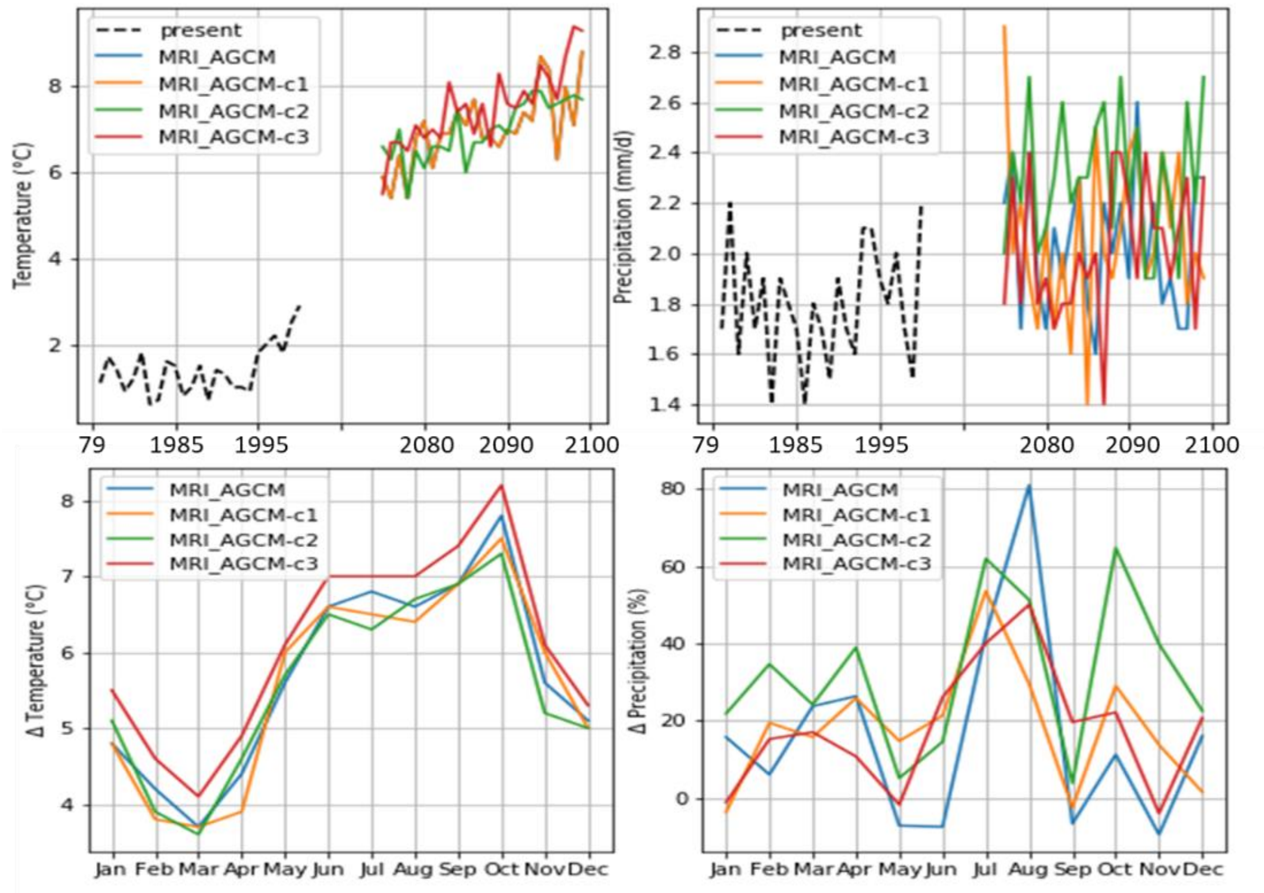

Figure 28: Top panel shows change in temperature and precipitation across UIB according to MRI-AGCM. Lower panel shows increase in temperature and precipitation on monthly basis.

Spatial trends in future temperature are comparatively uniform and increases across all scenarios are projected (Figure 29 a to 30 d). The warming in the months from July to September will be the highest (7–9 °C). This increase will result in higher quantities of glacier melt and ice loss.

Notably, winter temperatures (October–March) will increase by 5–6 °C, which will change the form of precipitation from snowfall to rainfall. This factor has also been highlighted by Lutz et al. (2016) and they have projected that this phase change in precipitation will result in an increase in rainfall runoff in these months.

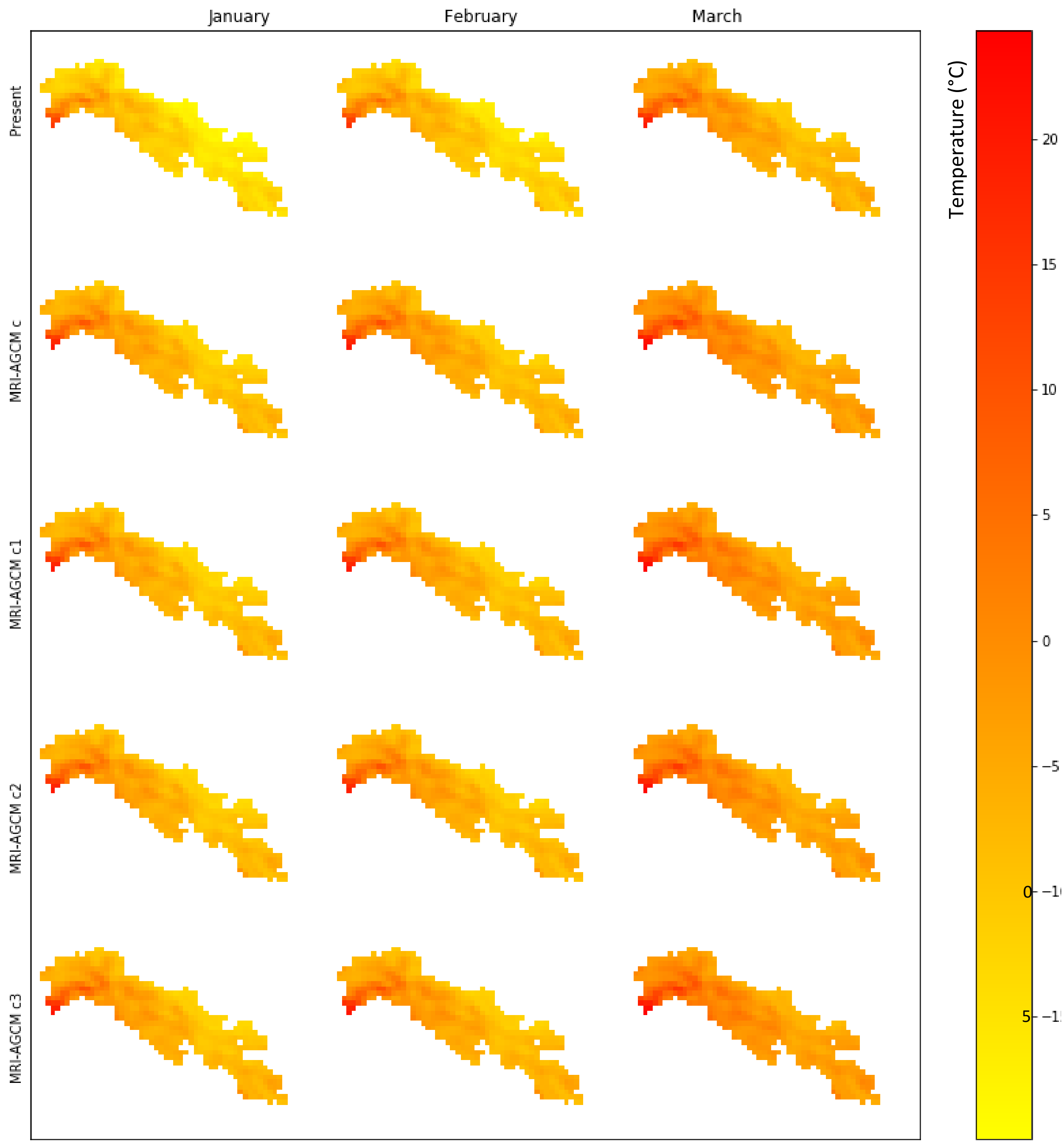

Figure 29 a: Future temperature across 4 MRI-AGCM scenarios in Jan-Mar.

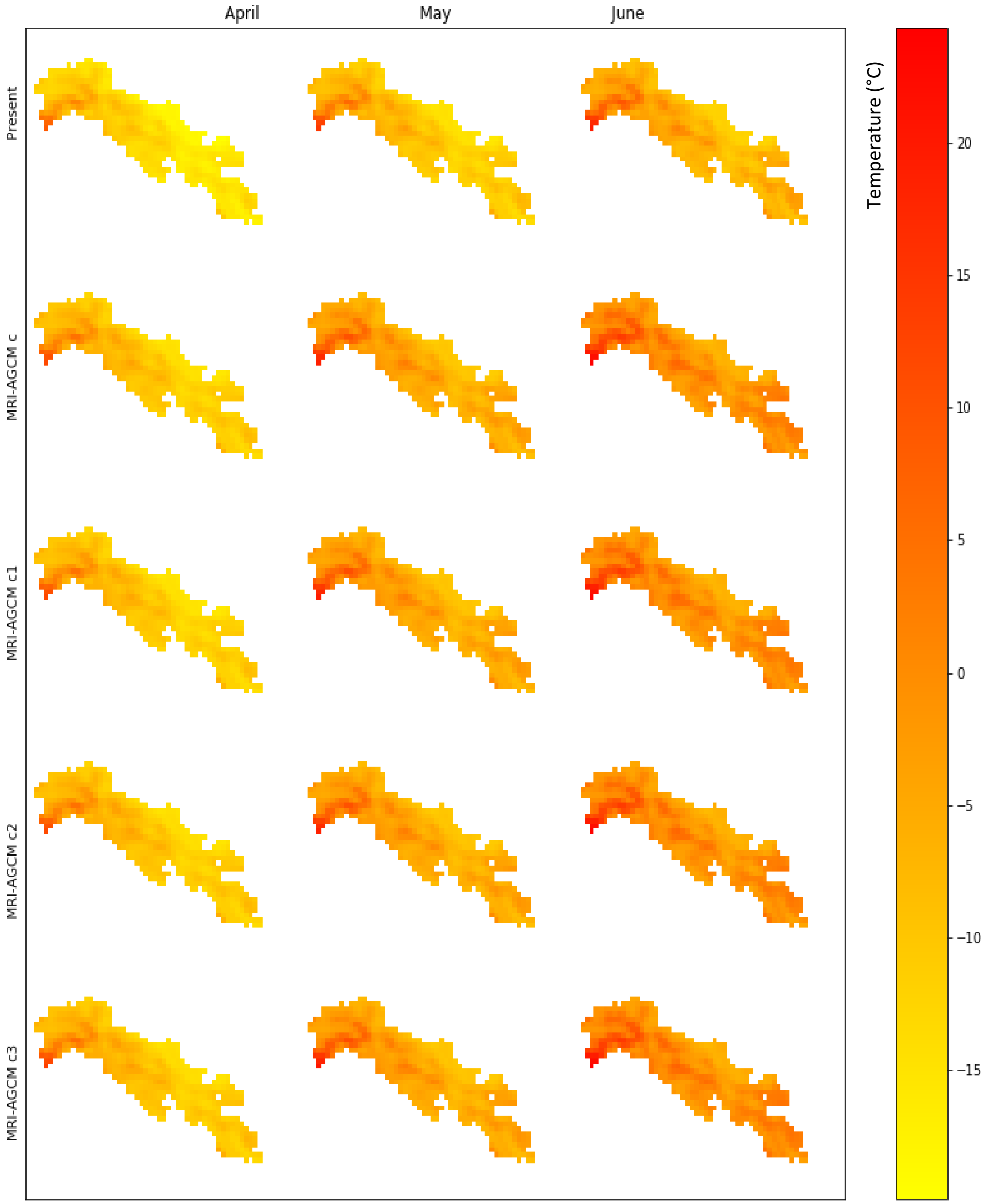

Figure 29 b: Future temperature across 4 MRI-AGCM scenarios in Apr-June.

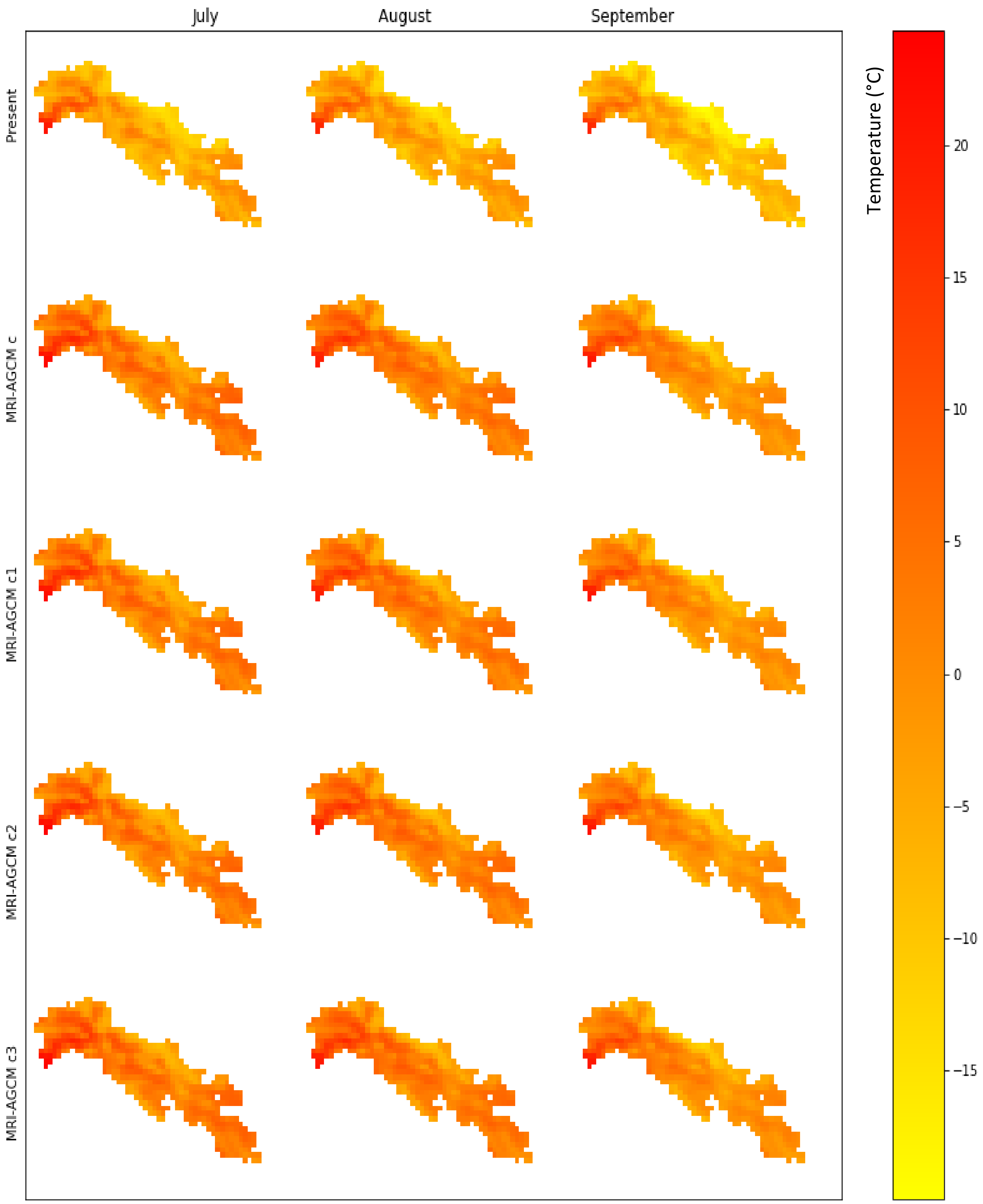

Figure 29 c: Future temperature across 4 MRI-AGCM scenarios in July-Sep.

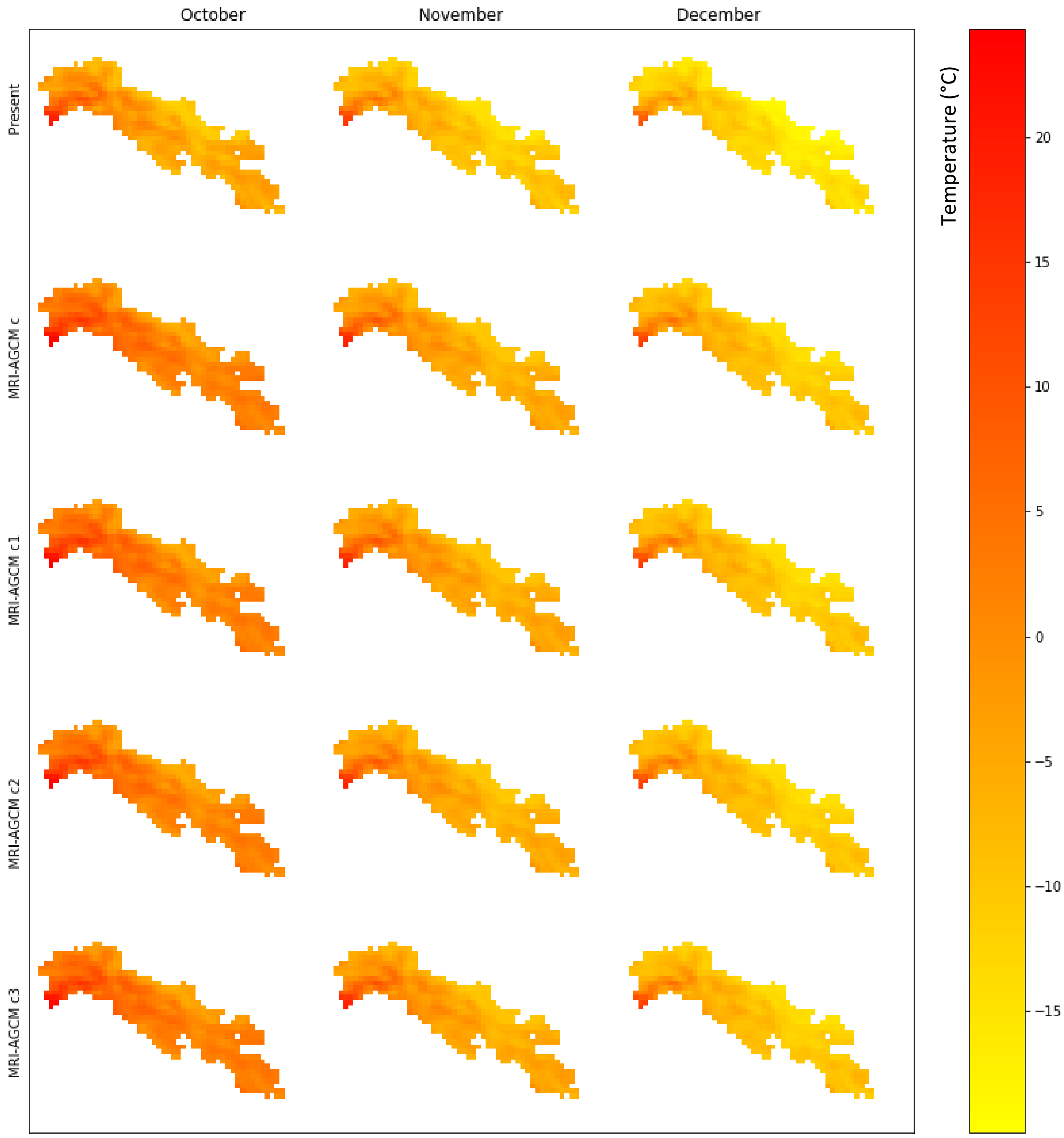

Figure 29 d: Future temperature across 4 MRI-AGCM scenarios in Oct-Dec.

On the other hand, the precipitation changes according to the MRI-AGCM scenarios are spatiotemporally variable. In winter (October–March), precipitation will increase at different magnitudes throughout the UIB. The eastern region of UIB is projected to have the highest increase of up to 100% in some areas. However, spatial variations have started to occur during April–September (Figure 30 a to d). Summer (July–September) will have a mixed trend across the UIB. The eastern region, which comprises of the Kharmong subbasin, will record higher precipitation during July–August (Figure 30 a to d). On the contrary, the northern region where the Shigar sub-basin is located will show a decrease in precipitation during the same season.

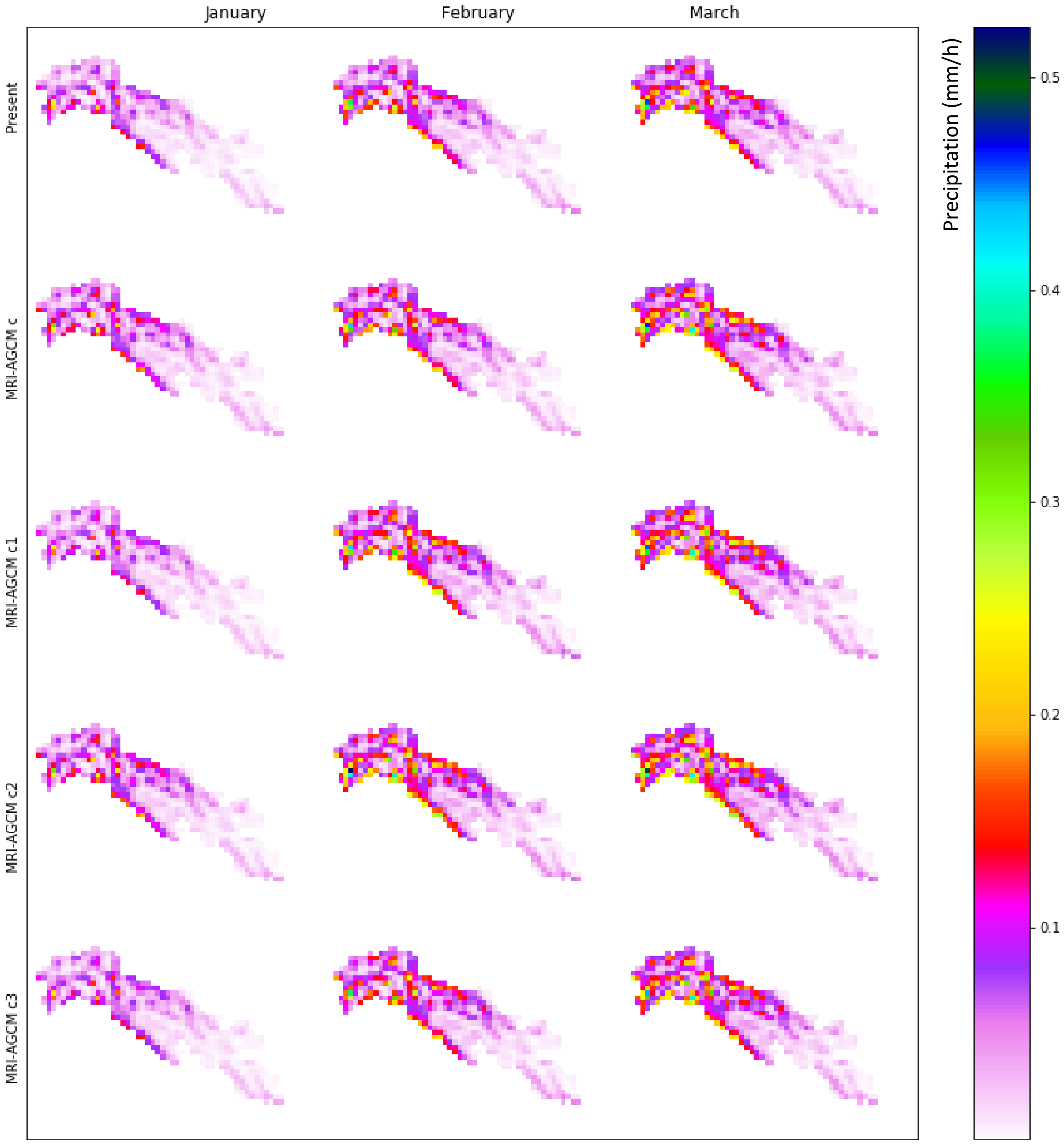

Figure 30 a: Future precipitation across 4 MRI-AGCM scenarios in Jan-Mar.

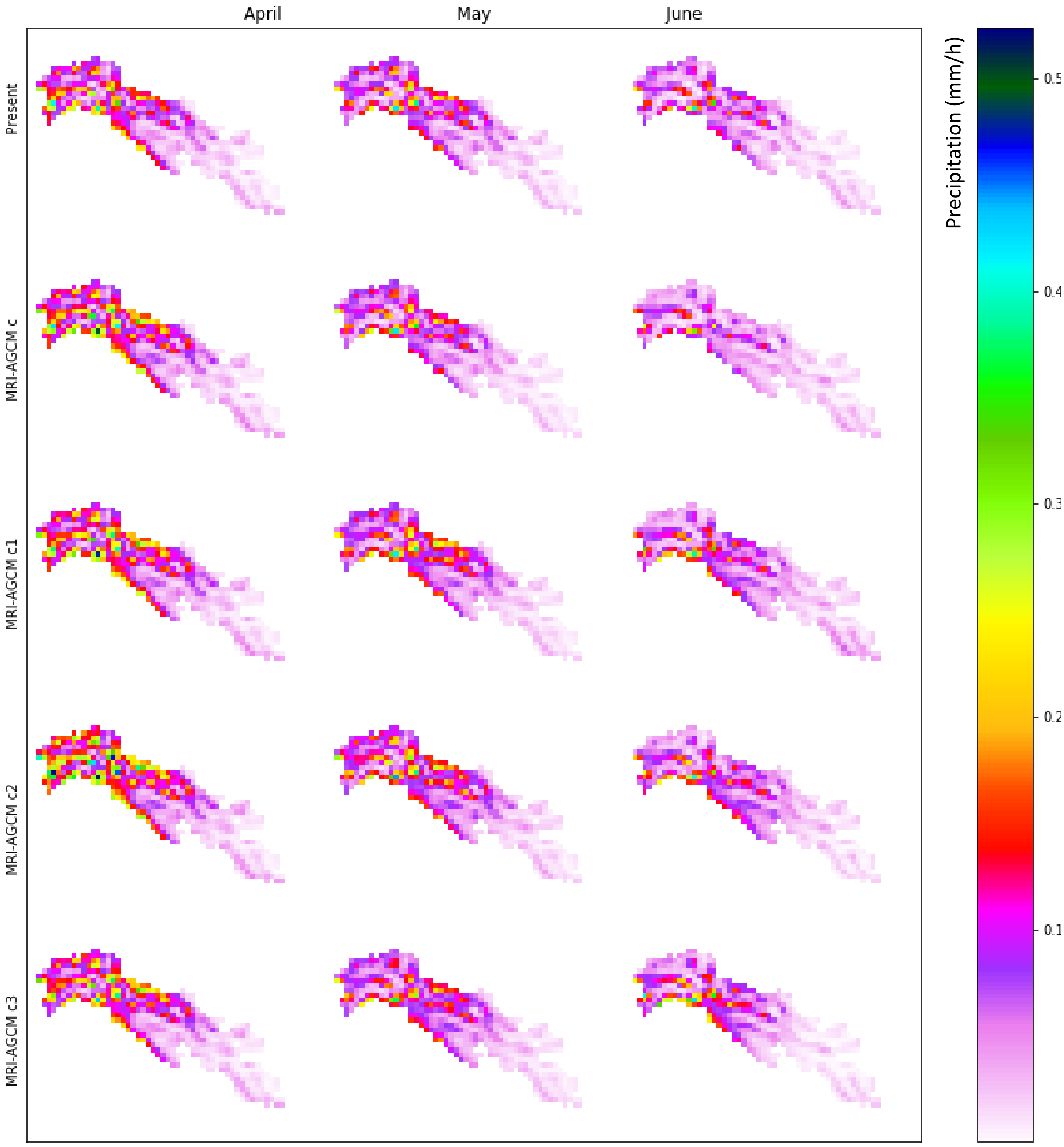

Figure 30 b: Future precipitation across 4 MRI-AGCM scenarios in Apr-June.

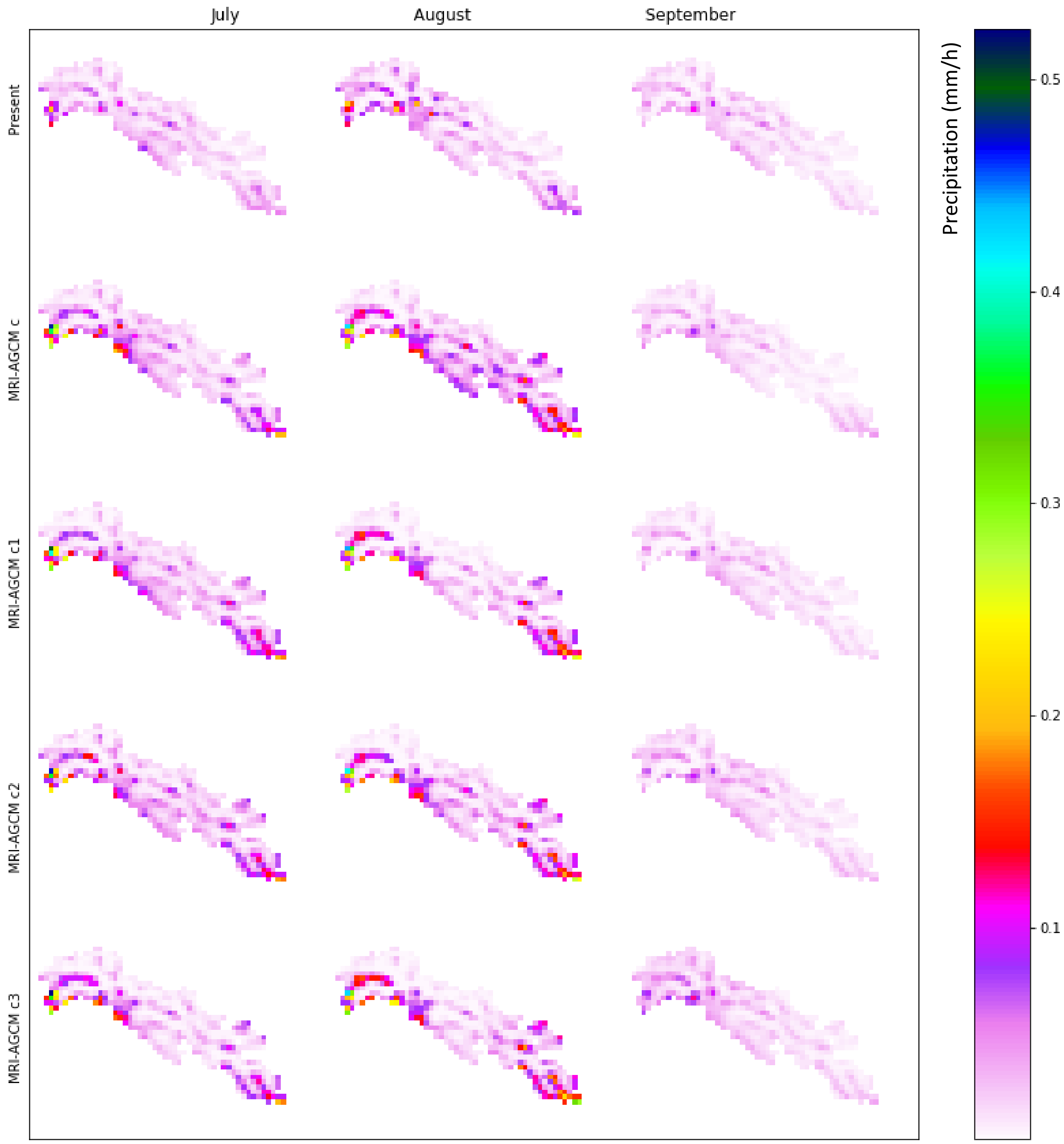

Figure 30 c: Future precipitation across 4 MRI-AGCM scenarios in July-Sep.

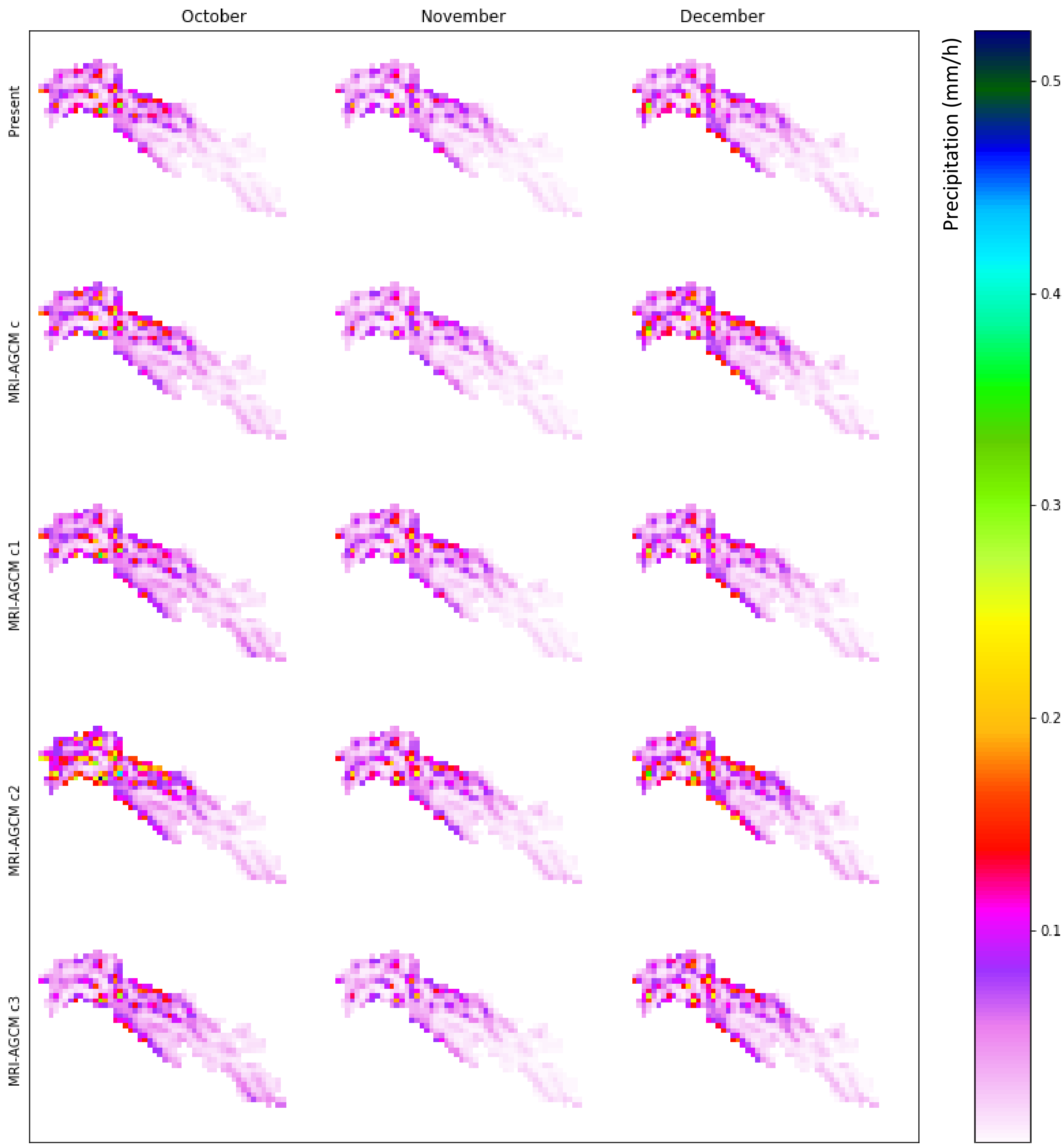

Figure 30 d: Future precipitation across 4 MRI-AGCM scenarios in Oct-Dec.

Figure 31 shows the projected monthly changes in climate in the UIB and its three sub-basins. There is a consensus among the scenarios in terms of temperature change in the three sub-basins. However, an insightful variability exists in the precipitation regime; Shigar will have an increase in precipitation during October–April in the future, and in Gilgit during July–September. Kharmong lies adjacent to the Himalayan mountain range, and it has a different precipitation regime, which is summer dominated as opposed to that of Shigar and Gilgit. The precipitation during July–August is projected to increase by 60–80% in the sub-basin.

In the UIB, precipitation will increase throughout the year; however, during March–April and July–August it will be significantly higher. This increase in precipitation will compensate for the loss of runoff because of glacier retreat in the UIB.

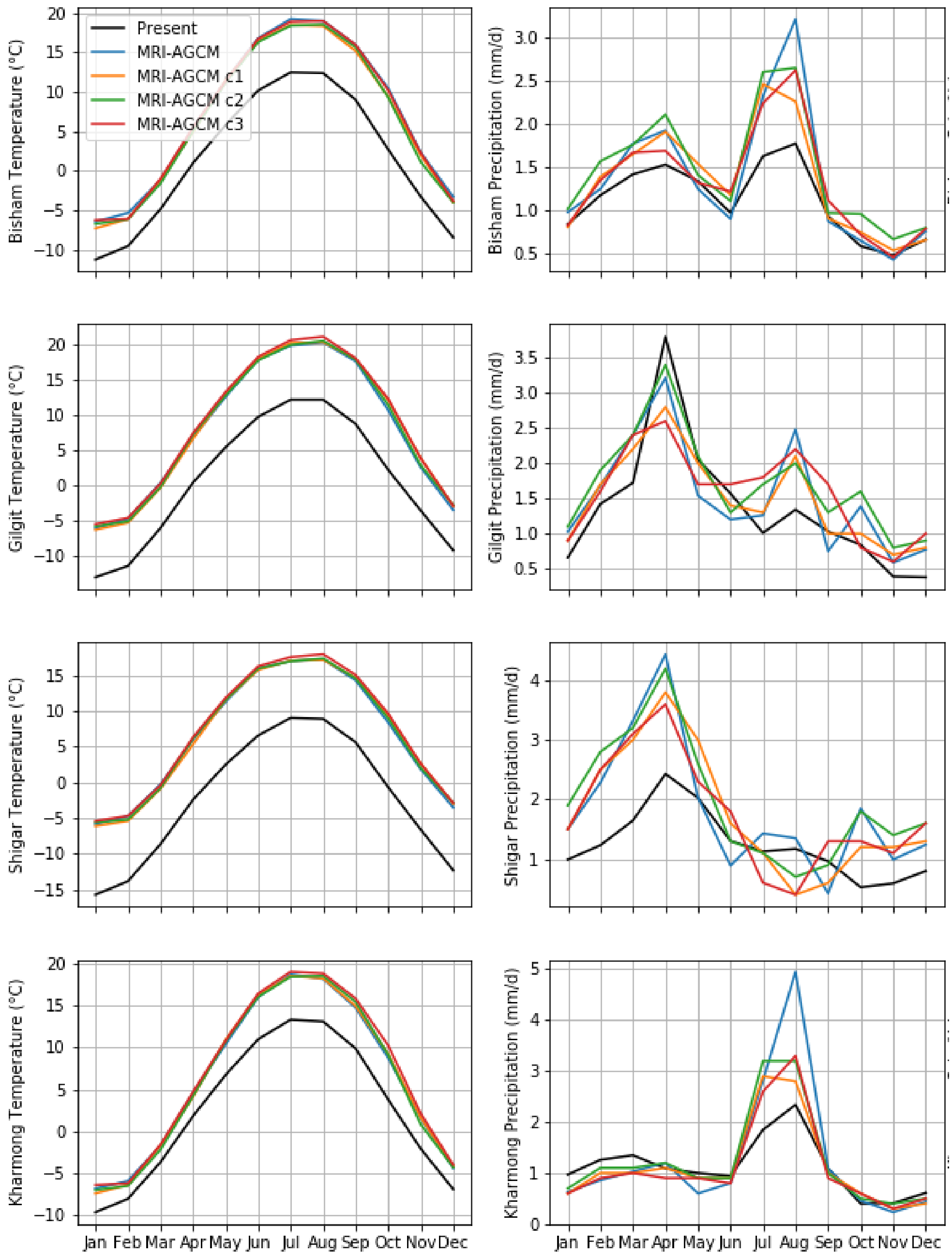

Figure 31: Change in climate in the sub-basins of UIB according to 4 MRI-AGCM scenarios.

5.6 FUTURE FLOW REGIME

Climate change will impact the peaks and quantities of the runoff components in the Bisham Qila and sub-basins. Figure 32 shows the seasonal alterations and shifts in the runoff components. Rainfall will increase across the basin, albeit with some differences in seasonal peaks. In the UIB, the spring and summer peak flows occur because of higher precipitation. These seasonal trends are evident in the sub-basins as well, but they have different magnitudes based on variations in precipitation (Table 15). There is a decrease in snowfall in the UIB and sub-basins because of the temperature increase resulting in its relatively lower proportion in precipitation. Overall, at the Bisham Qila station, the snowmelt runoff hydrograph will be reduced to half of its present value. Furthermore, the shape of the snowmelt runoff hydrograph is likely to reduce to three months, from mid-February to the end of April, in the future, while presently it lasts until June. Lutz et al. (2016) also reported a decrease in the contribution of snowmelt runoff in the future because rainfall will increase. Glacier retreat will cause various changes in hydrographs across the UIB because of changes in climate and topographic features of the UIB. In Gilgit, the glaciers will retreat to the extent that it will diminish their contribution to the hydrograph. Shigar will also experience a decrease in summer flows because of the retreat. On the other hand, Kharmong will have an excess contribution of glaciers to the hydrograph because its glaciers are located at higher elevations when compared to the other two sub-basins. This higher elevation will help sustain large glaciers and result in their increased contribution to the hydrograph in the sub-basin (Figure 32) and (Table 3).

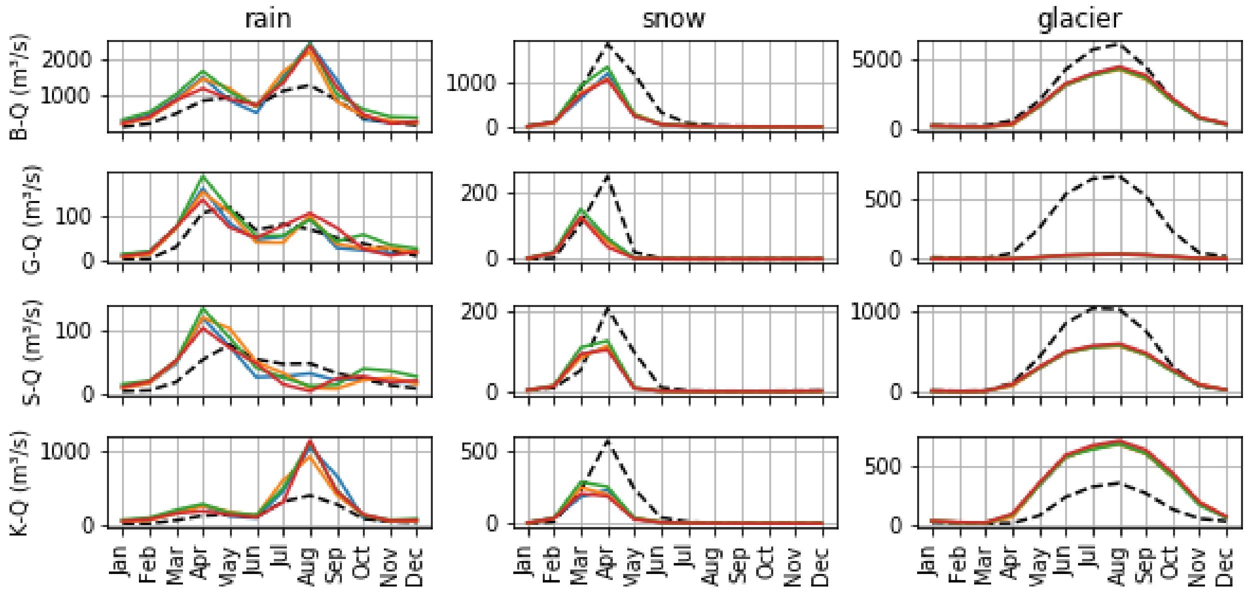

Figure 32: Comparison between present and future runoff components of UIB and sub-basins. Black line represents present and other colors MRI-AGCM simulations.

Figure 33 shows the future (2075–2099) and present (1980–2005) monthly river flows at the Bisham Qila station and its sub-basins. At the Bisham Qila station, the annual river flow in the future (2075–2099) will be 16% lower than that in 1980–2005. This decrease in the overall quantities is mainly due to the lower contributions from glaciers. Even intense precipitation during July–August across the UIB will not be enough to sustain the present river flows. The monthly river flows will decrease during May–August because of a reduction in the contribution of glaciers and lower precipitation during the May–June period. In winter and spring, river flows will increase because of increase in baseflow and seasonal precipitation. Other studies have also projected changes in future river flows in the UIB. For example, Lutz et al. (2016) stated that under RCP 4.5 and RCP 8.5 in the future (2071–2100), river flows in all seasons at the Bisham Qila station will increase, but winter flows will be substantially higher because of increase in rainfall during winter and an increase in corresponding base flow. Similarly, Hassan et al. (2019) reported an increase in summer river flows with a nominal increase in magnitude of 1–3% and relatively higher winter river flows.

Table 15: Summary of precipitation, temperature and runoff components in present (1980-2005) and future (2075-2099).

Present (1980-2005)								Future (2075-2099)						
Stations	P	T	Q	Glacier	Snow	Rain	Glacier %	P	T	Q	Glacier	Snow	Rain	Glacier %
Bisham	440	1.77	656	367	62	105	7.4	516	7.4	566	280	33	150	4.5
Gilgit	491	1.34	962	614	77	123	13	553	7.9	272	36	41	136	2
Shigar	450	-1.67	2400	1805	145	151	28.8	642	6.7	1640	1128	87	176	12.5
Kharmong	405	2.18	226	57	42	63	3.6	453	6.6	357	137	20	116	3.5

Gilgit and Shigar will be the most affected sub-basins in the UIB. Gilgit will experience a decrease every month except for March–April. Gilgit's river flows will decrease in the July–September period by 85%. Likewise, Shigar's river flows are also projected to decrease by approximately 45%; however, this is limited to the May–September period. Glacier retreat will cause decreases in future river flows of these two sub-basins (Table 15). Soncini et al. (2015) reported that, in the last decade of this century, the flows in the Shigar river basin will increase by 27% per annum because of precipitation and excess glacier melt. However, they also have reported a decrease in summer flows. The difference between our results and their study is in the future extents of glaciers that were used for simulations. The annual average river flows in Kharmong are projected to increase in the future as evidenced from the projected precipitation increase in each month. From July to September, river flows will increase up to 100% because of the combined effect of summer rainfall and glacier melt.

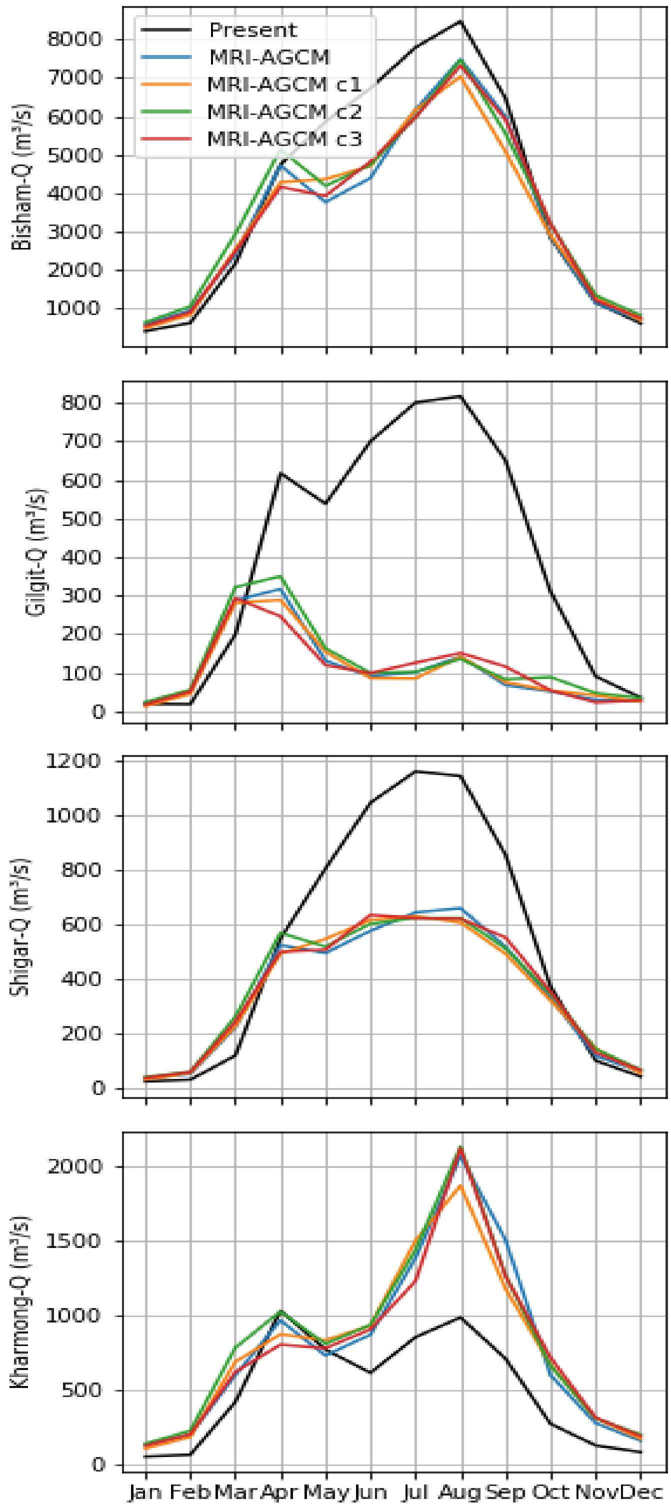

Figure 33: Change in the monthly river flows in future (2075-2099) with respect to present (1980-2005) at four stations across all climate scenarios.

5.7 CONCLUSION

The UIB is the major source of water for the agricultural and domestic water demands in Pakistan. Its climate is cold, and the precipitation regime is winter dominated. The annual precipitation is approximately 440 mm most of which falls in winter as snow. Due to the scarcity of observed climate data APHRODITE climate dataset is employed for hydrologic analysis. Temperature-index melt models have been used to calculate the snow and glacier melt in the UIB. The runoff is melt-water dominated, with an annual contribution of 80% by snow and glacier annually. The high share of melt-water in runoff is also true for all the sub-basins analyzed in this study.

The UIB's river flows are vulnerable to changing climate which will cause imbalance in the water supply-demand equation. For the assessment of the impact of future climate on the river flows, the MRI-AGCM with a spatial resolution of 0.1875° was used. MRI-AGCM has four scenarios based on different sea-level temperatures in the future (2075–2099). MRI-AGCM projected a precipitation regime that will have an increase of 60-80% during July– August. Besides this increase, precipitation in winter will also increase but with lower proportion. The average temperature throughout the UIB will increase by 5.36 °C from the present values in 2075–2099, and the highest temperature increase is projected to take place in September by 7–8 °C.

This increase in precipitation and temperature will alter the timings and quantities of the peaks flows in the UIB and its sub-basins. An increase in temperature will cause the glacier and snow, which are the major runoff sources to start melt early. More precipitation will occur as rainfall, and thus, the contribution of snowfall will decrease across the UIB. In the future (2075–2099), the contribution of snow will reduce to half of its present quantities in the UIB and its sub-basins. Rainfall will increase because of intense monsoons across the UIB, and this increase will be pronounced during March–April. The contribution of glaciers of the sub-basins towards flow will decrease except for in Kharmong where glaciers will not retreat because of their higher elevation. In Gilgit, the contribution of glaciers will almost become negligible when compared to their present contribution. Shigar will also record a reduction in glacier contribution, but it will be better than that in Gilgit. Overall, in the UIB, glacier contribution to flow will decrease by 25% when compared to the present glacier contribution. These changes in the climate and glacier-cover are projected to cause a drop in the annual river flows by 16%. The summer season will be the most affected because of drop in glacier contribution.

Although the simulations of river flows in the UIB and sub-basins were satisfactory and match well with that of other studies, several improvements are recommended. The precipitation datasets should be corrected using multiple precipitation extrapolation rates owing to the variability of climate in the basin. Moreover, improvements in melt models are crucial for the accurate accounting of snowfall, melt of glacier/snow and runoff generation. Glacier mass-balance models are thus, needed to be included in the simulations for future where glacier retreat will play a crucial role in the annual river flows. Inclusion of the fine resolution GCM has revealed an important pattern of future climate in the UIB in the form of intense summer rainfall. This rainfall will play crucial role in the dry season.

These alterations in the peaks in the runoff components will result in a reduction in the average annual river flows in the UIB. Seasonal changes are very important because they provide for irrigation, hydro-power generation, and storage from September to April, while there is an increasing imbalance in the demand-supply equation in the remaining months. The downstream regions will have to share this imbalance and adapt to the changes in timing and quantities.

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CHAPTER 6: CONCLUDING REMARKS

Climate and water resources of UIB are poorly understood; low-density of climate stations, difficult terrain and influence of weather patterns are the main reason. Climate data plays fundamental role in assessment of water resources and its sustainable supply and consumption. Sound knowledge of climate and hydrology ensures balanced supply-demand equation and eases stress on the water resources. It further helps in sustainable conservation of water resources, conflict mitigation and future demand management. The climate of UIB is generally cold and topography plays important role in the variation of temperature and precipitation. Precipitation increases with elevation and temperature decreases and weather variability over short distances is common. Winter precipitation is the major source of river flows, while summer monsoon rainfall has less significant effect in comparison. Summer temperature which are above freezing melt the snow and glaciers which results in higher river flows. UIB is a valuable source of fresh water, it supplements the growing water demands of the region and downstream areas. The river flows are higher in summer mainly due to the glacier and snow melt contribution. Annual average flow in the UIB is around 2400 m^3/s. In summer (June to September) the average flow is 7000 m^3/s, in rest of the months it is very low and remains around 450 m^3/s. The regional glacier reserves are an asset, they store water in the form of snow in winter and releases in summer as a result of melt process. This glacier melt water constitutes 68% of the current river flows, when combined with snow melt it reaches up to 85% of the annual flows. Rainfall has little weightage i.e. merely 14% and its flow regime is limited to August and September. Similarly, on the sub-basin level melt water has dominant role in the runoff except for Kharmong where rainfall takes lead.

Climate change is expected to alter the flow regime of the basin. The impact of which are highly variable in space and time. Temperature is projected to increase throughout the century which will cause retreat in glaciers and impact their contribution in the runoff. Temperature and precipitation show interesting spatial variations which will cause alterations in the peaks of hydrographs. Temperature will increase by 5.7 °C across the UIB while significant variations exist. Shigar will have the highest increase in the temperature (8.3 °C) and Kharmong will have 4.4 °C increase. September-October period will witness up to 8 °C increase. Precipitation on the other hand shows diverse trends in variability on spatial and temporal scales in UIB. Highest increase is projected to take place in the July-August season where up to 80% increase in the precipitation is expected and play a crucial role in runoff. Winter season from October-March will record higher precipitation but with lesser margin. From October-March entire UIB is projected to have higher precipitation albeit some low elevation regions will have decrease in precipitation. Spatially diverse trends in the precipitation are projected to take place from July-September season. Across eastern and low-elevation regions precipitation will increase up to 100% while decreasing in the central parts of the UIB.

Monthly precipitation time series in UIB will have two peaks like present i.e. in spring and summer. On sub-basin level different patterns in monthly precipitation time series are projected. These patterns reveal internal variation in the precipitation and hints at alteration of peak timings and quantities. Snow contribution will shrink because of change of precipitation from snow to rain. On the other hand, rainfall will increase across the UIB because of higher rainfall in summer. This increase will play vital role in the runoff generation which is evident from the hydrographs.

Glaciers on the other hand, will decrease in the Shigar and Kharmong because of retreat while in Kharmong it will increase. Overall in UIB the glacier contribution will decrease by 25% because of glacier retreat.

In UIB annual river flows in future (2075-2099) will be 16% lower than present (1980-2005) quantities. This decrease in the overall quantities is mainly because of the glacier contributions, even intense precipitation in July-August across UIB will not be enough to sustain the present river flows. Similarly, in Gilgit and Shigar the river flows will decrease while in Kharmong the annual river flows will increase. This different response of Kharmong is because of the increased glacier contribution and higher precipitation.

Similarly, in Astore river basin, which is located in the southern region of the UIB, climate change will impact river flows in a different manner. In the mid-century the average annual flow will increase because of enhanced glacier melt. however, by the mid-century the annual flows will decrease significantly because of 75% retreat in the glaciers. The decreased glacier extent will impact summer flows in negative manner, the flow in July and August will drop by 50%. Precipitation will increase in future, which will increase the contribution of snow melt and rainfall from present values.

These results partially match with other studies. Mainly the similarities are found in the decrease of snow contribution. Previous studies have reported mixed trends in the annual river flows with ranges between -15% to + 60% for UIB between 2071-2100. The differences between studies is because of the usage of climate data and modeling approach.

The results of the modeling studies indicate shortcomings and can be improved. The soil-water, deep groundwater recharge and hydraulic conductivity relation in the model needs improvements. Furthermore, fine-resolution climate data and inclusion of physical processes in glacier melt model will significantly improve the simulations.

These alterations in the peaks in the runoff components will result in reduction in the average annual river flows in the UIB. The variations in the sub-basin river flows will shape the future water management scenarios. Seasonal changes are important because they will provide potential for irrigation, hydro-power generation and storage in spring on the other hand, the summer will be stressful, the western river basins will be drier and eastern sub-basins will have excess runoff. The storage of excess runoff in the eastern region will be helpful in summer for basin-wide water management. In eastern region will also have increased risk of flooding and landslides because of precipitation in summer. On the other hand, such risks will reduce in the western regions because of lesser increase in summer precipitation.

In future a mass-balance glacier melt models will be employed to study the future runoff in greater detail. Furthermore, the extent of study area will be expanded to the Kabul river basin. Kabul river basin is located in the western side of the UIB and prone to the floods and droughts.