

Abstract

The Himalayan mountains are considered as water towers because of the massive potential of freshwater in glacier ice masses and seasonal snow. They have colossal potential to receive and store the snow during winter and provide fresh water during summer due to snowmelt. Moreover, these mountains have a significant role in regulating global and regional climate. Rapidly rising temperatures caused by global warming could be catastrophic for the people living in this region and downstream as the mountain glaciers are critical for fulfilling the downstream water and energy demand. Therefore, any changes in the climate could implicate widespread impacts on livelihoods as perennial water security and food security are largely dependent on the snow and glacier melt in this region. However, different sub-regions may have different impacts of global warming and, per se, different consequences. Therefore, the planning for adaptation and resilience to the impact of changing climate on water availability require projected estimates based on reliable scenarios.

Hydroclimate modeling over the Beas basin, situated in North-Western Himalayas, is attempted in his study to assess the change in hydrological fluxes under present and future climates. The objective of the thesis is broadly divided into four tasks that start with the sensitivity analysis of Weather Research and Forecasting (WRF) model towards the selected microphysics and cumulus schemes to assess the ability of precipitation simulation over the study region. Next, Glacier model was used to produce the glacier dynamics in the study region under the present and future climates. Next, WRF-Hydro was calibrated using the automatic approach. Lastly, the offline coupled system of WRF and WRF-Hydro was used to produce hydrological fluxes under present and future climates.

Firstly, WRF was set up with three nested domains, the outermost covering the whole Himalayas, the middle covering the whole of the North-West ranges of Himalayas, and the innermost concentrated to the study area. The six experiments with a combination of three microphysics and two cumulus schemes were performed. It was found that the precipitation along the Himalayan foothills (near to basin terminal) is underestimated by four out of six experiments. Only WSM6_BMJ (WSM6 microphysics and BMJ convection scheme) and MP8_BMJ (MP8 microphysics and BMJ convection scheme) were able to show a considerable amount of precipitation along these foothills. However, all six experiments showed high precipitation in the upstream region and the mountain peaks and ridges in North-Western Himalayas. During December-January-February (DJF), MP8_KF, MP3_BMJ, and MP8_BMJ have shown relatively lesser precipitation, however, WSM6_KF and WSM6_BMJ were found to have maximum precipitation. MP8_KF is found to have the least normalized standard deviation, along with a higher skill score than most of the experiments. Overall, MP8_KF could be considered reasonable because of its lesser deviation and better skill score. For June-July-

August-September (JJAS), four (MP3_KF, MP3_BMJ, MP8_KF, WSM6_KF) out of six experiments failed to show the precipitation features in downstream foot-hills at the basin terminal and northern slopes, having average precipitation much lower in comparison to observation. WSM6_BMJ has shown the highest correlation and best skill score, along with the least normalized standard deviation.

Next, The glacier dynamics were simulated and analyzed over the Beas basin (situated in the north-western Himalayas) for the present (1980–2015) and future climates (2006–2100) under RCP4.5 and RCP8.5 global warming scenarios. The Open Global Glacier Model was first calibrated over the study region and then conducted simulations for the present (forced by ERA-Interim) and future (forced by CMIP5 models) climates. For the present climate, the model simulations show that 50% of the total glacier volume (compared to 1980) is lost by 2011, with glacier area and volume showing a significantly decreasing trend, with higher fluctuations in the glacial area during recent decades. Future projections suggest 75% loss by 2040 \pm 2.5 years and \sim 90% loss by 2094 \pm 3.5 years under RCP4.5. Under RCP8.5, 75% loss is expected to occur by 2040 \pm 3 years and \sim 90% by 2084 \pm 8 years. Ensemble mean of the near-surface air temperature (both monthly mean and annual mean) shows a significantly increasing trend under RCP4.5 and RCP8.5 for the entire 21st century. Ensemble mean of the total monthly precipitation shows no trend under RCP4.5, however, it shows a decreasing trend for months OJFMA and an increasing trend for months JJ under RCP8.5. An increase in JJ precipitation does not increase glacier mass since this region does not receive snowfall during these months. Under RCP4.5, snowfall does not show any significant trend during NDJF, however, it shows a decreasing trend during October and March. Under RCP8.5, snowfall shows a significant decreasing trend for October through March. Overall, a similar melting rates were found under RCP4.5 and RCP8.5 until \sim 2050, but the latter shows a higher rate afterward.

Next, the WRF-Hydro calibration was performed using the WRF downscaled meteorological forcing. The model was calibrated for 2003 and validated for 2004-2005. The station observed discharge at the basin outlet was used to perform the calibration and validation. The selected 42 parameters were tuned using PEST (Parameter ESTimation) tool through the model inversion process. The eight simulations were designed using two sets of meteorological forcing (MP8KF forcing and WSM6BMJ forcing). It is found that model calibration improved the accuracy to reproduce the basin discharge. Despite improvement, JJAS discharge was underestimated in MP8KF experiments, possibly due to underestimation in the JJAS precipitation in MP8KF forcing. WSM6BMJ experiments did reasonably well for the JJAS, but it showed some erroneous high peaks for the non-JJAS. These peaks were probably introduced due to the overestimation of the precipitation (for non-JJAS) in WSM6BMJ forcing. Further, the best candidate out of these simulations was picked up, each for MP8KF and WSM6BMJ experiments. Then, the ensemble mean and weighted ensemble of the basin discharge was calculated from these best candidates. The ensemble mean discharge was found

reasonably well for the calibration period (NSE=0.64), however, the accuracy decreases for the validation period. The weighted ensemble of these simulations produces satisfactory results (NSE=0.5), alongside the accuracy increases for the validation period (NSE=0.6).

Next, the WRF with WRF-Hydro was coupled in offline mode. The convection permitting simulations were performed using the WRF model for high-resolution atmospheric forcing (for one historical time slice and three-time slices for future projections under RCP4.5 and RCP8.5). These atmospheric forcing were fed to the hydrological model (WRF-Hydro) to generate high-resolution hydrological fluxes. The updated glacier boundaries were obtained from the glacier model and subsequently ingested to the WRF and WRF-Hydro to represent an updated Land Use Land Cover (LULC). It was found that the total amount of precipitation over the basin does not change by large values in the basin, however, there is a significant contrast in the change of the precipitation pattern. The higher peaks and ridges of the basin are expected to experience lesser precipitation under both RCP4.5 and RCP8.5, having the largest decline for the end of 21st century under RCP8.5. In contrast to this, the downstream regions may get wetter in comparison to the historical time period. The contrast was found mostly because of the composite of the different responses during different seasons (DJF and JJAS). The near-surface air temperature is expected to rise throughout the annual cycle under RCP4.5 and RCP8.5 scenarios. Though RCP4.5 tends to stabilize post-2050, RCP8.5 continues to rise, leading to the significant difference between the temperature of these two scenarios post-2050. The study region is expected to become warmer by 1-3 °C under RCP4.5 and 3-4 °C under RCP8.5 for JJAS at the end of the 21st century. DJF is expected to become warmer by 2.5-3.5 °C under RCP4.5 and 4.5-5 °C under RCP8.5 at the end of this century. The surface runoff is expected to decrease almost throughout the basin. However, it was found to be increased over high peaks during early-21st-century under RCP4.5 and during mid-21st-century under RCP8.5. The largest decline was found at the end of this century under both RCP4.5 and RCP8.5 for higher altitude regions. The subsurface flow (UGDRNOFF) decreased consistently under both RCP4.5 and RCP8.5, with a stronger declining signal under RCP8.5. UGDRNOFF is expected to decrease by ~60% under RCP4.5 and ~70% under RCP8.5 at the end of this century. Under RCP4.5, the snow water equivalent (SNEQV) was found to be decreased for the regions having altitude lower than 5 km, however, the same is found to be increased for the higher elevated regions. A similar response is expected under RCP8.5 until the mid of 21st century, however, towards the end of the century, SNEQV is expected to decline throughout the year across the region. The highest decline in SNEQV could occur during the end of the 21st century for both RCP4.5 and RCP8.5 scenarios. The contrasting response of SNEQV under both scenarios at the end of this century could be because of the different levels of warming.