Assessing the snow cover dynamics and its relationship with different hydro-climatic characteristics in Upper Ganges river basin and its sub-basins

Sahadeep Thapa[1,3], Fan Zhang[1,2,3,4*], Hongbo Zhang[5,6], Zeng Chen[1,3], Wang Li[1,3], Chongyu Xu[8], Santosh Nepal[7], Amrit Thapa[7]

[1] Environment Change & Multi-sphere Interaction Team, State Key Laboratory of Tibetan Plateau Earth System Science, Institute of Tibet Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[2] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing, China

[3] University of Chinese Academy of Sciences, Beijing, China

[4] Kathmandu Center for Research and Education, Chinese Academy of Sciences-Tribhuvan University, Kathmandu, Nepal

[5] College of Water Resources & Civil Engineering, China Agricultural University, Beijing, China

[6] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing, China

[7]International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal

[8] University of Oslo, Oslo, Norway

Abbreviations:

GRB, Ganges river basin; UGRB, Upper Ganges river basin; UYRB, Upper Yamuna river basin; UGaRB, Upper Ganga river basin; SaRB, Sarada river basin; KaRB, Karnali river basin; GaRB, Gandaki river basin; KoRB, Koshi river basin

---

[*] Corresponding author. Tel.: +86-10-84097030; fax: +86-10-84097079; E-mail address: zhangfan@itpcas.ac.cn

ABSTRACT: Snowmelt is an important source of water in the upstream part of the Ganges river basin (GRB), which provides water for different purposes to its 655 million inhabitants. However, studies assessing relationship between snow cover dynamics and changes in hydro-climatic variables are limited within this region, which has motivated the current research. In this study, MODIS snow cover product (MOD10A1) was used to assess the snow cover area (SCA) dynamics within the Upper Ganges river basin (UGRB) and its sub-basins for the time period of 2002-2014; available climate and hydrological data were used to assess the hydrological characteristics within three selected sub-basins in Nepal; and relationships between snow cover and different hydro-climatic variables are established for three sub-basins owing to availability of hydro-climatic data. Results show that the average annual maximum SCA is around 24.6-47.5% for UGRB and its sub-basins. Upper Yamuna river basin (UYRB) with lowest mean elevation among the sub-basins shows a single SCA peak in spring within an annual cycle, whereas UGRB and the higher sub-basins show an additional lower peak in fall mainly resulted from snow sublimation. During 2002-2014, SCA shows slight decreasing trends for UGRB ($\tau = -0.039$) and the higher altitude zones B (3001 – 4500 m asl) and C (> 4500 m asl) of most sub-basins, with significance only in Zone C of SaRB ($\tau = -0.070$) and KoRB ($\tau = -0.062$). Annual discharge (all rivers) shows non-significant decreasing trends ($\tau = -0.359$ to -0.051) which are resulted from decreasing discharge in different seasons in different sub-basins. Seasonal correlation analysis indicates an important water supply from rainfall in Gandaki river basin (GaRB) and combined water supply from rainfall and snowmelt in Koshi river basin (KoRB), along with dominant contribution of precipitation in monsoon months and snowmelt in non-monsoon months for all the three sub-basins. Improved snow products with less effects of cloud cover and longer time series would help draw more robust conclusions related to SCA changes.

Keywords: Upper Ganges river basin, snow cover dynamics, hydrology, climate.

1. Introduction

High mountain areas of the world provide an important source of fresh water for large population in the adjacent lowlands (Bandyopadhyay et al., 1997; Liniger et al., 1998; Meybeck et al., 2001; Viviroli and Weingartner, 2004; Barnett et al., 2005; Viviroli et al., 2007). Glaciers in mid and low-latitude regions such as South American Andes, European Alps and high mountains of Asia (HMA) act as a water storage, which is important for human livelihood for purposes such as domestic use, hydropower production, irrigation for food production, especially in dry seasonal or interannual conditions (Hewitt, 2005; Masiokas et al., 2006; Bookhagen and Burbank, 2010; Immerzeel, 2010; Gardner et al., 2013; Haeberli and Colin, 2017; Marty et al., 2017).

Climate change is expected to affect water resources within the mountainous river basins, especially when warming is expected to be higher at the higher altitude, i.e., the elevation dependent warming (Kotlarski et al., 2012; Gobiet et al., 2014; Pepin et al., 2015). Higher temperatures can cause decrease in the snowfall by changing its form to liquid precipitation and decreasing the snow cover duration (Barnett et al., 2005; Mote, 2006; Brown and Mote, 2009; Magnusson et al., 2010; Bavay et al., 2013). The reduction in snow cover and changes in precipitation can affect the timing and availability of water resources in the downstream regions, especially in the spring season, when the river runoff is more likely to be dominated by snowmelt (Smith et al., 2017).

Owing to the importance of the snow cover in the mountain regions, it is essential to understand the snow cover dynamics in the high mountain regions. There is generally a lack of stations in the higher elevation regions for monitoring the snow dynamics due to reasons such as inhospitable climate, harsh terrain etc (Saloranta et al., 2019). In this case, the remote sensing datasets has been used as an alternative to monitor the snow cover dynamics in these regions. Among various datasets, MODIS snow cover products have been used in monitoring the snow cover dynamics in many parts of the world. The MODIS/Terra (MOD10A1) and MODIS/Terra (MOD10A2) snow cover product have the same spatial resolution (500 m) whereas they differ in the temporal resolution with the MODIS/Terra (MOD10A1) snow cover product having a resolution of a single day and MODIS/Terra (MOD10A2) snow cover product having a resolution of 8 days. MODIS/Terra (MOD10A2) is derived from the 8 day periods of the MODIS/Terra (MOD10A1) daily snow cover product (Shrestha et al., 2015). Parajka and Blöschl (2006) used the daily MODIS/Terra MOD10A1 snow cover product and compared these with the ground snow depth observations over Austria and reported an accuracy on average of 95% on cloud free days. Klein and Barnett (2003) used the daily MODIS/Terra MOD10A1 snow cover product and compared these with the operational snow cover maps produced by the National Operational Hydrologic Remote Sensing Centre (NOHRSC) and in situ Snowpack Telemetry (SNOTEL) measurements over the Upper Rio Grande River Basin in southern Colorado and northern New Mexico and reported an accuracy of 86% when the MODIS snow cover product was compared with the snow cover maps from the NOHRSC and 94% when the MODIS snow cover product was compared with the in-situ SNOTEL measurement, over a snow season. Pu et al. (2007) used the in-situ snow observations from the Tibetan Plateau (TP) and compared those with 8 day MODIS/Terra (MOD10A2) snow cover product and reported an accuracy of 90%. Yang et al., (2015) used the MODIS/Terra (MOD10A1) snow cover product over the TP and compared it with the station observations and Landsat Thematic Mapper (TM) images and reported an accuracy of 91% against the station observations and 79% against the Landsat TM images. Tahir et al. (2011) used the fine resolution ASTER data and compared it with 8 day MODIS/Terra (MOD10A2) snow cover product over Hunza river basin and reported an accuracy of 75%, 95% and 99% at lower, middle and higher altitudes, respectively. These validations of MODIS snow cover product suggest that it can be used to assess the snow cover dynamics in absence of field data in the high mountain regions.

Among the major rivers originated from the Himalayan region of HMA, the Ganges river provides water resources for a large population (Amarasinghe et al., 2016; Rasul, 2009; Sadoff and Nagaraja, 2014). Within the Upper reaches of the river basin, i.e. Upper Ganges river basin (UGRB), there are six major sub-basins namely, Upper Yamuna river basin (UYRB), Upper Ganga river basin (UGaRB), Sarada river basin (SaRB), Karnali river basin (KaRB), Gandaki river basin (GaRB) and Koshi river basin (KoRB) (Fig. 1). Snow, glaciers and permafrost dominate the headwater region, with precipitation falling in the form of snow all year round (Nepal and Shrestha, 2015), and snow and glaciers are important sources of water for the upstream sub-basins (Viste and Sorteberg, 2015). Within the upper parts of KaRB, GaRB, and KoRB in Nepal, the annual contribution of snowmelt and glacier melt to river discharge is estimated to be about 20% - 34% (Bookhagen and Burbank, 2010; Nepal et al., 2017). Siderius et al. (2013) also pointed out that within the higher elevation region of UGRB, the contribution of snowmelt and glacier melt was even higher. For example, in the Bhagirathi catchment of UGaRB, the average snowmelt and glacier melt contribution to the total river discharge was around 96% for the ablation period (May to September) of 2005 (Prakash et al., 2019). The air temperature in the sub-basins of UGaRB, KaRB, GaRB and KoRB has been reported to be increasing (Sharma et al., 2000; Khatiwada et al., 2016; Nepal, 2016; Sharma and Ojha, 2018; Chand et al., 2019). These increases may lead to changes in forms of precipitation from snowfall to rainfall, earlier shifts and subsequent decrease in snowmelt, and increases in glacier melt in the near future and subsequent decrease in the far future, which in turn can lead to overall changes in river flow regime within this region (Shiwakoti, 2012; Neupane et al., 2014; Nepal et al., 2014, 2016). Snow cover mapping in UGRB has been taken into account by Gurung et al. (2011) and Muhammad and Thapa (2020), but without considering the possible effects of climate change on snow cover dynamics and correlation between the snow cover dynamics and hydro-climatic variables.

Owing to the importance of the snowmelt and the possible effects of the climate change on snow, precipitation and river flow regime in UGRB, the objectives of this study include: (a) to analyze the spatio-temporal changes in the snow cover within different elevations of UGRB and the six sub-basins, (b) to evaluate the annual and seasonal trends of hydro-meteorological variables (discharge, temperature and precipitation) within three sub-basins of UGRB (i.e. KaRB, GaRB and KoRB); and (c) to establish the annual and seasonal correlation between the snow cover area (SCA), mean temperature, precipitation and river discharge within the three sub-basins of UGRB. The novel features of this study include assessing the snow cover dynamics over a longer time period (2002 – 2014) for UGRB and the six sub-basins, and assessing the relationship between snow cover and hydro-climatic variables within the three sub-basins considering the data availability.

<insert **Figure 1**>

2. Study area

The Ganges river, originating from the high altitude areas of the Himalayas, is one of the major rivers of Asia, provides water for different purposes such as drinking, agriculture, hydropower generation, navigation and ecosystem. About 655 million people inhabit across the river basin, which is about 1 million square kilometers (Amarasinghe et al., 2016; Rasul, 2009; Sadoff and Nagaraja, 2014). About 25,000 MW of electricity could be potentially generated through hydropower projects existing and under construction or planning phases within the upstream mountainous region of the basin (Bharati et al., 2011; Sadoff and Nagaraja, 2014). It is a trans-boundary river basin and flows through China, Nepal and India into the Indo-Gangetic Plain (Nepal and Shrestha, 2015). It merges with Brahmaputra in an extensive delta region in India and Bangladesh, after which it enters Bay of Bengal. Rainfall is the highest contributor to discharge as compared to the snowmelt and glacier melt (Lutz et al., 2014). The main features of UGRB and its sub-basins are given in Table 1. UGRB lies in the western and central Himalayan region, with an average elevation of 3312 m above sea level (a.s.l.). The sub-basins UGaRB, SaRB, KaRB, GaRB and KoRB lie in central Himalayas with average elevations of 3416, 2795, 3333, 3020, 3794 m a.s.l., respectively, whereas UYRB lies in western Himalayas with an average elevation of 2137 m a.s.l.. For the three sub-basins in Nepal, the mean annual air temperature, precipitation, and runoff depth calculated from sub-basin areas are 18.3~20.1 °C, 1412.4~2521.6 mm/yr, and 710.8~1195.7 mm/yr, respectively.

<insert **Table 1**>

The hypsometric curve and percentage area under each 500-m altitudinal layer estimated from SRTM-DEM for UGRB and its sub-basins are presented in (Fig. S1). Of all the sub-basins, KoRB has the highest mean elevation and the largest (~30.5%) percentage of area above 4500 m a.s.l, and UYRB has the lowest mean elevation and the smallest (~0.4%) percentage of area above 4500 m a.s.l.

3. Materials and methods

A brief description of datasets and methods used for the current study is given below.

3.1 Topography

The Shuttle Radar Topography Mission – Digital Elevation Model (SRTM -DEM), from the original resolution of ~90 m was resampled to a resolution of ~ 1 km and used to delineate the watershed boundary for UGRB. The boundaries between the six sub-basins of UGRB were taken from HydroBASINS, which is a series of polygon layers for basins and sub-basins at different scales around the world. The watershed boundaries for the HydroBASINS are delineated using the HydroSHEDS database at the resolution of ~450 m and the sub-basins are further delineated using the Pfafstetter coding system. For the current study, the sub-basins have been used from Level 5 of the HydroBASINS.

The elevation of UGRB varies from 26 m to 8435 m a.s.l. The topography consists of lowlands in the lower elevations to numerous mountains, including Mt. Everest. Thus, a basin scale approach may not be suitable to assess the snow cover dynamics within UGRB. It is necessary to understand the snow cover dynamics in different elevations of UGRB, which in turn could give us a better understanding of hydrology regimes in the upstream catchments, and water resources management with relation to different purposes such as drinking, agriculture, hydropower generation and eco-system services. Three different altitudinal zones were extracted from the resampled SRTM-DEM for the detailed analysis of snow cover dynamics in UGRB and its sub-basins. The area of total catchment and each altitudinal zones within the catchment along with mean and median elevations and hypsometric curves were estimated using the resampled SRTM-DEM (Table S1).

3.2 Hydrometeorology

The hydro-climatic stations shown in Fig. 1 are used for the current study within the three sub-basins (KaRB, GaRB and KoRB) in Nepal. The Department of Hydrology and Meteorology (DHM) in Nepal carries out the hydro-meteorological measurements at different locations within Nepal. The earliest observations date back to 1962 for air temperature, 1947 for precipitation and 1962 for discharge. For this study, data from earliest observations up to 2016 were provided by DHM. For KaRB and GaRB, the air temperature and precipitation data are available up to 2016 and discharge data are available up to 2015. For KoRB, the air temperature and precipitation data are available up to 2016 and discharge data are available up to 2014. Analysis is therefore carried out for the period of 2002 to 2014 when both SCA and hydro-meteorology data are available for the three sub-basins. There are some data gaps in the precipitation and air temperature measurements carried out by DHM. In the KaRB, based on daily data, the percentage of missing values ranges from ~1.3% to ~8.9% and ~6.3% to ~43.5% for precipitation and air temperature respectively. In GaRB, based on daily data, the percentage of missing values ranges from ~1.9% to ~8.7% and ~4.4% to ~53.9% for precipitation and air temperature respectively. For KoRB, based on daily data, the percentage of missing values ranges from ~1.3% to ~2.3% and ~0.6% to ~63.1% for precipitation and air temperature respectively. These data gaps for precipitation and air temperature measurements have been filled using the data from the Global Land Data Assimilation System (GLDAS 2.1) (Rodell et al., 2004). GLDAS 2.1 data contain 36 land surface fields from January 2000 to present day. The data are available in a temporal resolution of 3 hours and a month. For precipitation, the 3 hourly values have been summed into daily values. For air temperature, the maximum and minimum values are extracted from the 3 hourly daily data.

Climate (precipitation and air temperature) and discharge data were analyzed using the regression analysis to investigate hydro-meteorological change trends. Precipitation data were the average annual total precipitation for all the stations for a sub-basin whereas air temperature data were the average of annual average air temperature for all the stations for a sub-basin. Trend analysis on the standardized values of mean annual runoff and mean annual precipitation was also carried out. Standardized values were calculated using the normal deviate formula of calculating the distance of each data point from mean of the data distribution and dividing it by standard deviation of the data distribution (Tahir et al., 2015). To identify the trends in time series data, non-parametric Mann-Kendall (MK) trend test (at a significance level of 5%) (Kendall, 1975; Mann, 1945) and linear regression analysis were carried out. The values of the trend test and slope are the Kendall's Tau (τ) coefficient and slope (m) respectively. MK test is one of the most widely used non-parametric tests for assessing the trends in hydro-meteorological time series data (Burn, 2008; Burn et al., 2010; De Freitas, 2020; Li et al., 2020). As compared to other trend tests, this test has an advantage of robustness against the departures from normality within the data. It is also less affected by outliers and independent from the initial hypothesis about linear or non-linear trend of the data. Seasonal analysis for winter months of December, January and February (DJF) and summer months of June, July and August (JJA) was also carried out.

Furthermore, an analysis of relationship between annual and seasonal values of different variables (SCA, total precipitation, mean temperature and discharge) was also carried out. Kendall's rank correlation (Kendall, 1975; Kendall and Gibbons, 1990), Pearson's product moment correlation (Rodgers and Nicewander, 1988) and Spearman rank order correlation (Spearman, 1904) tests were performed at significance level of 5% to analyze the relationship between these variables and analyze the main factors controlling discharge at outlet points within each sub-basin.

3.3 Snow cover

The Moderate Resolution Imaging Spectro-radiometer (MODIS) snow product was used to assess the snow cover dynamics within UGRB and its sub-basins. The MODIS/Terra Snow Cover L3 Global 500m SIN Grid V006 (MOD10A1), used for the study, contains gridded snow cover and albedo derived from radiance data acquired by the MODIS on board the Terra satellite. The snow cover is identified using the Normalized Difference Snow Index (NDSI) and a series of screens which are designed to lower the errors and flag uncertain snow cover detections. The data covering the whole of the river basin were downloaded from the National Snow and Ice Data Center (https://n5eil01u.ecs.nsidc.org) for the time period of January 2002 to December 2014.

UGRB and its sub-basins were then extracted for estimating the snow cover (%) in the study area over the 13-year period. The MODIS snow products within certain grid cells may contain a significant percentage of cloud which if not removed may lead to significant uncertainties about the actual estimation of the snow cover (Hall et al., 2019). In this study, if an image contained more than 15% of cloud cover on a single day, then it would be excluded from the analysis (Tahir et al., 2015). The snow cover during this gap was then estimated using linear interpolation between previous and next cloud free images. Maximum snow cover over 8 days of daily data was used for our study. Snow cover was also estimated for the three altitudinal bands for UGRB and each sub-basin to examine the spatio-temporal trends of snow cover within these areas. SCA was estimated as the percentage of total land area for the river basins and the altitudinal zones. After processing the images for the removal of grid cells with cloud cover, regression analysis was carried out as done for the meteorological and discharge data, using non parametric Mann-Kendall (MK) trend test (at a significance level of 5%) and linear regression. The framework of this study is given in Fig. 2.

<insert **Figure 2**>

4. Results and discussion

4.1 Changes in snow cover area in UGRB and its sub-basins

Fig. 3 shows the average percentage of 8-day maximum SCA for UGRB and the six sub-basins. The multi-year average annual maximum percentages of SCA are ~32.9%, 25.6%, 47.5%, 39.5%, 24.6%, 34.8%, and 25.4% for UGRB and its sub-basins UYRB, UGaRB, SaRB, KaRB, GaRB and KoRB, respectively. The different percentages of SCA in UGRB and its sub-basins could be resulted from the difference in precipitation and air temperatures under the influence of the climate systems and elevations. In the most western part of the Himalayas, i.e., near the Karakoram region, the influence of westerlies is more than that of the summer monsoon. Westerlies have been known to deposit solid precipitation in form of snow during winter, such as in the Hunza sub-basin of the upper Indus river basin (Tahir et al., 2011). In this region, under weak summer monsoon influence, more clear weather can cause an increase in the snow and glacier melt, resulting in a higher value of runoff from snow and glaciers (Mayer et al., 2014). This combined with the lowest elevation and thus potentially higher temperature could be the reason for the lower SCA in UYRB and the higher SCA in the eastern and higher sub-basins. This can also be seen in the form of glacier covered areas, with UYRB having the least glacier coverage among the sub-basins (Table 1).

<insert **Figure 3**>

Based on the climatic conditions of the study area, there are four seasons, namely pre-monsoon, monsoon, post-monsoon and winter. Considering snow dynamics, a year can be classified into snow ablation/melt period and snow accumulation period (Meetei et al., 2020). The time period from April to September with higher air temperature is usually considered as the ablation/melt period and the time period from October to the following March with snowfall events and lower air temperatures is considered as the accumulation period in the Himalayan region, resulting in a SCA peak around March (Jain et al., 2009; Tiwari et al., 2015; Bothale et al., 2015; Ahluwalia et al., 2016). In this study, SCA in UGRB shows two distinct accumulation periods. The first accumulation period starts from January and peaks during mid-February to late March whereas the second starts during September and peaks during late October to mid-November. Snow ablation occurs after mid-March and reaches the lowest value in late June to early September. Snow ablation also occurs after late October but this is lower as compared to snow ablation after first snow accumulation period. The sub-basins UGaRB, SaRB, KaRB, GaRB and KoRB in central Himalaya also show two distinct accumulation periods with slightly different timing compared to UGRB, whereas UYRB in west Himalaya with lowest mean and median elevation (Table 1; Fig. S1) shows only one accumulation period starting from September and peaking around January to February and one subsequent ablation period within an annual cycle.

Fig. 4 shows multi-year average percentage of 8-day maximum SCA in three altitudinal zones for UGRB. The annual maximum SCA percentage is highest in zone C (~31.1%), followed by zone B (~16.5%) and zone A (~1.0%), subsequently. Due to the altitudinal difference and air temperature lapse rate, major form of precipitation in zone A occurs as rainfall, and zone C is highly glaciated. Highest percentage of SCA in zone C could also be due to the lowest air temperature and highest snowfall in this zone. In the highest altitudinal zone C of UGRB, SCA shows two distinct accumulation periods. First accumulation period starts during January and peaks in mid-March to late March whereas second one starts from September and peaks in end of October and early November. The peak during first accumulation period is higher as compared with peak during second accumulation period. In the lower altitudinal zone A and zone B of UGRB, SCA shows only one accumulation period starting from December and October, respectively, and peaking around mid-February and one subsequent ablation period ending by mid-May and early June, respectively, within an annual cycle. Zone A has lower altitude than Zone B, and thus higher air temperature, later accumulation but earlier ablation.

<Insert **Figure 4**>

The results of two accumulation periods and SCA peaks within annual cycle are different from most previous studies (Jain et al., 2009; Tiwari et al., 2015; Bothale et al., 2015; Ahluwalia et al., 2016) but similar to that of a small catchment named Nuranang in eastern Himalayas (Bandyopadhyay et al., 2015), which could be possibly due to the difference in elevation, air temperature and precipitation of different catchments, or use of different datasets and the different study periods. In addition, another possible reason for the snow mass loss during winter could be snow sublimation. Although the months of January and February are usually the snow accumulation months along with lower air temperature, static snow sublimation (SSS) and blowing snow sublimation (BSS) could be significant. Low air humidity, high solar radiation and strong winds, which is a characteristic of high mountain regions, can result in high snow sublimation rates (Gasocin et al., 2013). At Niwot Ridge in Colorado, 15% of maximum accumulated snow accounted for SSS in a snow season (Hood et al., 1999). In the alpine Berchestgaden National Park in Germany, SSS was modeled to account for ~20% of the winter snow fall (Strasser et al., 2008). At a high alpine region in Binggou basin in TP, Zhou et al., (2013) simulated the seasonal SSS loss to be at ~23.4% of the total snow fall. At a location in the Himalayan glacier in Nepal, Stigter et al., (2011) estimated the SSS loss to be at 21% of the annual snow fall. During the blowing snow conditions, exchange of energy and mass between snow surface and air masses above can occur efficiently (Pomeroy and Gray, 1995), especially in places where fresh snow is available and wind is accelerating such as at mountain ridges (Strasser et al., 2008). Winter snowfall can also be reduced by a substantial amount during BSS, reducing the snow depth and snowmelt runoff in spring. In the study by Strasser et al., (2008), BSS accounted for ~ 4% of the winter snowfall, which had a high local significance. In the study by Zhou et al., (2014), BSS accounted for about ~24.0% of the total snowfall during snow accumulation season. Blowing snow transport can also be an important form of snow mass loss in these regions (Gascoin et al., 2013). It has been suggested that wind can scour the snow from the non-glaciated surfaces and deposit it in the glacier areas, increasing the net mass balance of the glaciers (Gascoin et al., 2011). Gascoin et al., (2013) showed that the wind transported snow from non-glacier areas deposited more preferentially in the glaciated areas.

Based on a global atmospheric lapse rate of -0.65°C/1000m (Dobrowski et al., 2009), an increase of 2.5 – 4.5°C over the next 100 years (Giese et al., 2007; Meehl and Stocker, 2007) would mean that there would be a rise of 400 – 700 m in the 0°C isotherm. Rise in the elevation of the 0°C isotherm means that there is less space available for intercepting snowfall, causing a significant decrease in snow volume. This will have effects on those basins, especially whose area in zone C is less such as UYRB and SaRB. For the whole UGRB, SCA shows a slight decreasing trend, with Kendall's Tau value of -0.039, which however is non-significant for the period of 2002-2014 (Table S2). The changing trends of SCA for each altitudinal zone of UGRB and each sub-basin are given in Table S3. The higher Zone B and Zone C with higher SCA of most sub-basins indicate decreasing trends but only significant in Zone C of SaRB and KoRB. Table S2 shows the temporal trend of SCA in UGRB and its sub-basins for winter, spring, summer and fall months during 2002-2014. SCA values in UGRB and its sub-basins mostly show decreasing trends during winter months (i.e., the snow accumulating period) but increasing trends during spring and summer months. However, none of these slight decreases and increases are significant.

The probable explanation for the slight decreasing trend of snow cover in UGRB and all its sub-basins, especially in the high elevation zone, could be due to the decreasing trend in winter precipitation. For the KaRB, GaRB and KoRB, winter precipitation has shown a decreasing trend (Table S2). Another possible explanation for the decreasing trends of the snow cover could be the elevation dependent warming (EDW), which has been suggested by a number of studies, such as by Pepin and Lundquist (2008), Liu et al. (2009), and Qin et al. (2009) and recently supported by the Mountain Research Initiative EDW Working Group (2015). The EDW with higher warming rate at higher elevations has been reported to be associated with the reduction of snow cover of the higher altitudes of the river basins in the Tibetan Plateau and surrounding mountain region, namely Indus river basin, Yarkant river basin, Salween river basin and Brahmaputra river basin (Li et al., 2017).

4.2 Changes in annual runoff in sub-basins of UGRB in Nepal

As shown in Table 1, the average air temperature is highest for the KaRB whereas for GaRB and KoRB, the average air temperature values are nearly equal. Average annual runoff is highest for GaRB, followed by KaRB and KoRB, which is in the same order of precipitation in the three sub-basins. Fig. 5 a-c show the mean monthly average air temperature, mean monthly precipitation, and mean monthly runoff depth during 2002-2014 for the three sub-basins in Nepal where hydro-meteorological data are available. Air temperature shows lowest values of 10 - 12 °C in winter, with a gradual increase during spring and a stable maximum of 23 - 25 °C in summer, after which it shows a continuous decrease in fall and early winter for all the three sub-basins. Precipitation shows low values in winter, followed by increase in spring and summer, with peak value in July or August, after which it shows a decrease in fall. Runoff shows lower values in winter and spring, after which it shows a sharp increase from May, with peak value in August, after which it shows a sharp decrease. The timing of precipitation and runoff peaks are synchronized in KaRB but slightly differ between in GaRB and KoRB. The one-month delay of runoff peak compared with the precipitation peak could be partly due to the runoff generation and routing processes. In addition, runoff peak in August could also be due to the intensive glacier melt from the glacierized part under high solar radiation and high air temperatures (Thayyen and Gergan, 2010). These kind of precipitation and runoff patterns, i.e. with peak values in summer are characteristic of monsoon dominancy which is in contrast with the western part of the Himalayas, which experience less summer monsoon precipitation (Bookhagen and Burbank, 2006). In the Karakoram region, two peaks of discharge in spring and summer have been clearly visible on the flow hydrograph (Li and Williams, 2008), with snow melt dominant regime in spring and glacier melt in late summer (Thayyen and Gergan, 2010).

<insert **Figure 5**>

Table S4 shows the values of seasonal average air temperature, seasonal total precipitation, and seasonal average runoff depth. Air temperature and runoff are both the lowest in winter and highest in summer among different seasons. Seasonality of precipitation is not consistent among the sub-basins. Summer precipitation is the highest for all the sub-basins, while spring precipitation is lowest for KaRB and winter precipitation is lowest for GaRB and KoRB.

Fig. 5 d-f show the results of trend analysis for standardized values of mean annual air temperature, mean annual precipitation, and mean annual runoff during 2002-2014. For KaRB, GaRB and KoRB, runoff shows decreasing trends of -0.054 mm/yr, -0.107 mm/yr and

-0.096 mm/yr, when precipitation shows increasing trends of 0.088 mm/yr and 0.062 mm/yr but decreasing trend of -0.035 mm/yr, and air temperature shows a decreasing trend of -0.095 °C/yr but increasing trends of 0.126 °C/yr and 0.257 °C/yr, respectively. For KaRB, the runoff shows a decreasing trend with a Kendall's Tau value of -0.051, precipitation shows an increasing trend with a Kendall's Tau value of 0.179 and temperature shows a decreasing trend with a Kendall's Tau value of -0.333. For GaRB, the runoff shows a decreasing trend with a Kendall's Tau value of -0.231, precipitation shows an increasing trend with a Kendall's Tau value of 0.154 and temperature shows an increasing trend with a Kendall's Tau value of 0.385. For KoRB, the runoff shows a decreasing trend with a Kendall's Tau value of -0.359, precipitation shows a decreasing trend with a Kendall's Tau value of -0.333 and temperature shows an increasing trend with a Kendall's Tau value of 0.590. The trend is only significant for annual temperature in KoRB whereas all other trends are not significant. Table S2 shows the trends in seasonal runoff, precipitation, and air temperature. For KaRB, decreasing annual runoff is mainly resulted from decreasing spring runoff (-2.602 mm/yr) related to decreasing of both spring precipitation (-0.085 mm/yr) and spring air temperature (-0.245 °C/yr) and decreasing fall runoff (-4.028 mm/yr) related to decreasing fall air temperature (-0.098 °C/yr). For GaRB, decreasing annual runoff is mainly resulted from decreasing spring runoff (-3.037 mm/yr) related to decreasing spring precipitation (-0.105 mm/yr). For KoRB, decreasing annual runoff is mainly resulted from decreasing summer runoff (-13.145 mm/yr) related to decreasing summer precipitation (-0.264 mm/yr).

The trends are significant for winter and spring runoff and summer air temperature for GaRB, spring runoff, summer precipitation, and spring, summer and fall air temperature for KoRB whereas all other trends are not significant. It is inferred that the significant decreasing trend of winter runoff in GaRB could be due to decreasing trend of winter precipitation. Less winter precipitation probably means that there could be less snowfall and subsequent snowmelt available for river discharge. The correlation between changes in SCA and discharge for non-monsoon period will be further analyzed in Section 4.3. Although the spring temperature shows a significant increasing trend in KoRB, significant decreasing trend of spring runoff in KoRB could be due to decreasing trend of winter precipitation and slight decreasing trend of spring precipitation, which resulted in less snow available for melt.

4.3 Correlation between seasonal snow cover, climate variables and runoff in the KaRB, GaRB and KoRB

Fig. 6 shows the relationship between standardized values of multi-year seasonal SCA, precipitation (P), air temperature (T) and discharge (Q). In KaRB, correlation doesn’t show any significant values between any of the variables. In GaRB, discharge shows a significant positive correlation with precipitation, indicating a significant contribution of rainfall to river discharge. The correlation between discharge and precipitation is also highest among the three sub-basins. Correlation between other variables doesn’t show any significant values here. In KoRB, precipitation shows a significant negative correlation with temperature, indicating a decrease in snowfall under the overall warming background. Discharge shows a significant positive correlation with precipitation, indicating a significant contribution of rainfall to river discharge. In addition, discharge also shows a significant negative correlation with SCA, indicating additional contribution of snowmelt to river discharge. The absolute correlation between discharge and SCA is highest among the three sub-basins. Correlation between other variables doesn’t show any significant values. For KaRB, Khatiwada (2016) showed that rainfall, snowmelt, glacier melt and baseflow contributed to ~59%, ~13%, ~13% and ~15% of total discharge, respectively. For GaRB, rainfall, snowmelt, glacier melt and baseflow contributed to ~44%, ~9%, ~13% and ~34% of total discharge, respectively (Nepal et al., 2017). For KoRB, average of smaller catchments indicated that rainfall and snowmelt contributed to ~38% and ~13% of total flow, respectively (Khadka et al., 2020). These modeling results confirm that both rainfall and melt water are important for discharge in these sub-basins.

<insert **Figure 6**>

Correlations between monthly differences in P and monthly differences in Q for the monsoon months (June, July and August) are given in Fig. 7 a-c. These two variables are positively correlated with significant values, in all the sub-basins, with highest values for GaRB, followed by KoRB and KaRB, indicating dominant contribution of monsoon precipitation to summer discharge. Correlations between monthly differences in SCA and monthly differences in Q for the non-monsoon months are given in Fig. 7 d-f. These variables are negatively correlated with significant values, in all the sub-basins, with highest values for KoRB, followed by GaRB and KaRB, indicating the important contribution of snow melt to discharge in non-monsoon season with less rainfall.

<insert **Figure 7**>

Within major rivers in Nepal, summer discharge has been attributed to summer monsoon rainfall (Sharma, 1997; Thapa and Pradhan, 1995). The study by Neupane et al. (2014) indicated that monsoonal stream discharge would be higher in the Kali-Gandaki catchment of GaRB due to projected increases in precipitation and glacier melt. In another study by Pradhananga et al. (2014), it was indicated that in Langtang catchment of GaRB, future flows would increase in the pre-monsoon season due to increase in temperature and earlier shifts in flow occurred due to increases in temperature and precipitation. In KaRB, in the study conducted by Dahal et al. (2020), it was indicated that the precipitation amount will increase in the pre-monsoon and monsoon months, increasing the river discharge. These studies indicate that monsoonal intensification; increases in temperature and conversion of snowfall to rainfall are the causes for the increases in river discharge of most smaller catchments in KaRB, GaRB and KoRB. Within UGRB, in the study conducted by Wijngaard et al., (2017), it was indicated that the future mean discharge and high flow conditions will likely increase towards the end of the 21st century, which could be mainly due to the increase in precipitation extremes and somewhat increase in temperature extremes as well, with low flow conditions occurring less frequently, although there are uncertainties in the low flow projections.

4.4 Possible effects of changes in water availability in water use sectors

There are many projects related to water use such as hydropower generation and irrigation which exist or are in the planning/construction phase in the three sub-basins of Nepal. The three major river systems in Nepal along with their tributaries provide a production capacity of ~50,000 megawatts (MW) of electricity (Alam et al., 2017). Within GaRB, the existing hydro-power projects include Kali Gandaki A, Trishuli, Devighat, Chilime, Mailung Khola, Tadi Khola and Thoppal Khola hydropower projects whereas there are 7 others under construction and 23 planned. Out of these, except for the Kali Gandaki A hydropower project, others lie in the Trishuli sub-basin of GaRB (Tendolkar et al., 2020). The Kali Gandaki A hydropower project has an installed capacity of 144 MW of electricity and has a dam height of 43 m (Thanju, 2008). Within the Trishuli sub-basin of GaRB, the existing hydropower projects amount to a total installed capacity of 81 MW, with highest capacity for Trishuli hydropower project (24 MW) and lowest for Thoppal Khola hydropower project (2 MW), the projects under construction amount to a total of 286 MW, with highest capacity for Rasuwagadhi hydropower project (111 MW) and lowest for Upper Mailung A hydropower project (6.42 MW) and the planned projects amount to a total of 1163.6 MW, with highest for Upper Trishuli hydropower project (216 MW) and lowest for Salankhu khola hydropower project (2.5 MW). The another proposed one is the Budhi Gandaki hydropower project, with an installed capacity of 1200 MW and dam height of 265 meters (Ghimire, 2018). The irrigation potential for GaRB is about 1.1 million hectares in India and 0.4 Million hectares in

Nepal (Nepal, 2017). The current amount of water allocated for the irrigation is already being reduced owing to effect of reduced rainfall in dry season, and reduction in winter rain has forced the farmers to stop growing the winter crop (Dandekhya et al., 2017). In KoRB, in 1985, the Koshi river master plan study had been carried out for assessing the hydropower and irrigation potential of the basin and identified 52 hydropower project sites with minimum capacity of 10 MW, out of which 36 were located in Sunkoshi basin and potential irrigation in Terai region of KoRB, having an estimated area of 474,800 hectares (ADB, 2019). These projects also included multi-purpose schemes with both hydropower production and irrigation such as the Sunkoshi to Kamala diversion, and high dam projects such as the Sapta Koshi High Dam project. Some studies such as the one by CIWEC (1998) have suggested expanding the irrigation area to a net area of 602,000 hectares. The current irrigation schemes in KoRB include the Kankai irrigation scheme covering an area of 80 sq. km., Sunsari Morang irrigation scheme covering an area of 680 sq. km, Western Koshi irrigation scheme covering an area of 355 sq. km., Kamala irrigation scheme covering an area of 250 sq. km. and Bagmati irrigation scheme covering an area of 300 sq. km. whereas the current hydropower projects in KoRB include the Panauti hydropower project (2.4 MW), Sun Koshi hydropower project (10.5 MW), Indrawati hydropower project (7.5 MW), Khimti hydropower project (60 MW) and Bhote Koshi hydropower project (Shrestha, 2015). Saptakoshi high dam, with a height of 269 m, was designed aiming to control the floods in India and Nepal, provide irrigation to about 546,000 hectares of land in Terai district of Nepal and generate 3000 MW of electricity (skhdmp.gov.np). All these existing and planned projects within these basins, which are dependent on water from snowmelt, glacier melt and rainfall, can be largely affected by possible changes in water availability owing to climate change in these basins.

4.5 Uncertainty of changes in snow cover

Cloud cover is a major source of uncertainty for MODIS snow products, which can gather and block the information on the ground on any given day (Hall et al., 2010). The MODIS snow cover product applied in this study uses Normalized Difference Snow Index (NDSI) to identify the snow cover in the ground. NDSI can separate the snow from most obscuring or heavy clouds, however, it can’t accurately separate the clouds that are optically thin or light, resulting in misclassification of thin cloud as snow cover (Gurung et al., 2011). Although the gaps of data for consecutive 8-day maximum SCA have been interpolated in this study, there may be longer data gaps due to cloud cover, which introduce more uncertainty in snow cover change analysis.

There are daily cloud free snow cover products which have been developed to accurately monitor the snow cover on the ground. For example, in the study by Yu et al., (2015), a new product based on combination of MODIS Terra (500 m), MODIS Aqua (500 m) and Interactive Multisensor Snow and Ice Mapping System, IMS (4 km) had been developed, and whose accuracy when compared with ground station observations was 94% in all sky conditions as compared with 64% of combined MODIS Terra-Aqua’s, 55% of MODIS Terra’s, and 50% of MODIS Aqua’s in the TP, which unfortunately does not fully cover UGRB. More accurate product with similar or higher spatial resolution of MODIS, if available in the future for the study area, is suggested to be used to provide more accurately snow cover information. The current time series of MODIS data is kind of short, snow cover data of longer time series may help draw more robust conclusions.

.

4.6 Uncertainty of changes in discharge

The discharge data we have used in the current study can also be a source of uncertainty, particularly during the high flood time. In Nepal, during the flood peaks, the discharge is estimated using the rating curve. The rating curves used for this purpose are calculated from a few measurements carried out particularly during the low flow periods. These values are in a range of 30-600 m3/s, which is equivalent to a river level of about 1-4 m. During the flood peaks, when the flow volume of the river is high, the discharge values are estimated from the extrapolation of these low flow values. Within the Himalayan region, the stage discharge relationship may be based on an inadequate number of measurements, which will therefore be a major source of uncertainty (Kattelmann, 1987). Also, the discharge is measured 3 times a day, in 08:00, 12:00 and 16:00. However, the precipitation can also fall in the night time due to the clouds formed in the day time being condensed in late evening and night time, causing higher values of discharge in the night time. These factors can result in the uncertainty in the current measurement of discharge.

5. Conclusions

The following conclusions can be derived from the results of the current study:

The average annual maximum SCAs are around 24.6% to 47.5% for UGRB and its sub-basins UYRB, UGaRB, SaRB, KaRB, GaRB and KoRB. For the three sub-basins in Nepal, annual discharge is highest for GaRB, followed by KaRB and KoRB, which is in the same order of precipitation in the three sub-basins.

Two peaks of SCA in spring and fall separately are seen during an annual cycle in UGRB and its sub-basins UGaRB, SaRB, KaRB, GaRB and KoRB with higher mean and median elevations, and its highest altitude zone C of >4500 m asl, while only one peak in winter is seen in its lowest sub-basin UYRB and its lower altitude zones A and B. For the three sub-basins in Nepal, air temperature, precipitation, and discharge indicate obvious seasonal changes with single peaks in summer for air temperature, one peak in July for GaRB and KoRB and two peaks in July and August for KaRB for precipitation, and two peaks in July and August for GaRB and KoRB and single peak in August for KaRB for runoff.

The changes of annual snow cover during 2002-2014 show slight decreasing trends for UGRB (τ=-0.039) and the higher altitude Zones B (τ = -0.040 to -0.023) and C (τ = -0.070 to -0.016) of most sub-basins. For UGRB, the SCA varies from ~32.9% to 0%. For Zone B, the SCA for the basins with decreasing trend varies from ~87.9% to 0% and for zone C, the SCA for the basins with decreasing trend varies from ~98.7% to ~1.6%. Seasonal SCA in UGRB and its sub-basins mostly show non-significant decreasing trends during winter months but increasing trends during spring and summer months. Improved snow products with less effects of cloud cover, additional meteorological observation in high altitudes, and longer time series of data are needed for more robust conclusions.

For all of the three sub-basins in Nepal, annual discharge shows non-significant decreasing trends. Multiyear seasonal discharge shows a significant positive correlation with precipitation in GaRB (Spearman's correlation = 0.53) and KoRB (Spearman's correlation = 0.29), and significant negative correlation with SCA in KoRB (Spearman's correlation = -0.33). With consideration of seasonal changing trends, decreasing annual discharge for KaRB (τ = -0.051) is mainly resulted from decreasing spring discharge (τ = -0.256) related to decreasing of both spring precipitation (τ = -0.179) and spring air temperature (τ =-0.385) and decreasing fall discharge (τ = -0.205) related to decreasing fall air temperature(τ = -0.128); decreasing annual discharge for GaRB (τ = -0.231) is mainly resulted from decreasing spring discharge (τ = -0.590) related to decreasing spring precipitation (τ = -0.256); while decreasing annual discharge for KoRB (τ = -0.359) is mainly resulted from decreasing summer discharge (τ = -13.145) related to decreasing summer precipitation (τ = -0.615). For the monsoon months (June, July and August), monthly differences in discharge are significantly and positively correlated with monthly differences in precipitation in all the three sub-basins, while for the non-monsoon months, monthly differences in discharge are significantly and negatively correlated with monthly differences in SCA.

Acknowledgments

This study was funded by the “Strategic Priority Research Program” of the Chinese Academy of Sciences (XDA20060202), the National Natural Science Foundation of China (42001064), and the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute (2019nkms02). A special acknowledgement should be expressed to Kathmandu Center for Research and Education (KCRE), Chinese Academy of Sciences-Tribhuvan University, which support the implementation of this study and Department of Hydrology and Meteorology, Nepal for providing the climatic and hydrological data for this study.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

ADB. Managing Nepal's Dudh Koshi Rover System for a Fair and Sustainable Future 2019.

Amarasinghe UA, Muthuwatta L, Surinaidu L, et al . Reviving the Ganges Water Machine : potential 2016; 1085–1101.

Ahluwalia RS, Rai SP, Gupta AK, et al. Towards the understanding of the flash flood through isotope approach in Kedarnath valley in June 2013, Central Himalaya, India. Nat. Hazards 2016; 82: 321–332.

Alam F, Alam Q, Reza S, et al. A Review of Hydropower Projects in Nepal. Energy Procedia 2017; 110: 581–585.

Barnett TP, Adam JC, Lettenmaier DP. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 2005; 438: 303–309.

Bandyopadhyay A, Bhadra A, Chiphang N, et al. Assessment of Snowmelt Runoff in the Eastern Himalayan Region under Climate Change Scenarios. J. Indian Geophys. Union 2015; 312–321.

Bandyopadhyay JD, Kraemer R, Kattelmann and Kundzewicz, ZW, Highland waters: A resource of global significance, in Moun- tains ofthe World: A Global Priority. 1997; 131–155, Parthenon, New York

Bavay M, Grünewald T, Lehning M. Response of snow cover and runoff to climate change in high Alpine catchments of Eastern Switzerland. Adv. Water Resour. 2013; 55: 4–16.

Bharati L, Lacombe G, Gurung P, et al. The impacts of water infrastructure and climate change on the hydrology of the Upper Ganges River Basin, IWMI Research Report 2011; 142.

Bookhagen B, Burbank DW. Toward a complete Himalayan hydrological budget : Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge 2010; 115: 1–25.

Bookhagen B, Burbank DW. Topography , relief , and TRMM-derived rainfall variations along the Himalaya. Geophys. Res. Lett. 2006; 33: 1–5.

Bothale RV, Rao PVN, Dutt CBS, et al. Detection of snow melt and freezing in Himalaya using OSCAT data. J. Earth Syst. Sci. 2015; 124: 101–113.

Brown RD, Mote PW . The response of Northern Hemisphere snow cover to a changing climate. J. Clim. 2009; 22: 2124–2145.

Burn DH. Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. J. Hydrol. 2008; 352: 225–238.

Burn DH, Sharif M, Zhang K . Detection of trends in hydrological extremes for Canadian watersheds. Hydrol. Process. 2010; 1790: 1781–1790.

Dudh Koshi Hydroelevtric Project: Feasibility Study. Kathmandu: Nepal Electricity Authority, Canadian International Water and Energy Consultants (CIWEC) 1998

Chand MB, Bhattarai BC, Baral P, et al. Trend Analysis of Temperature Data for Narayani River Basin , Nepal. Sci 2019; 1–21.

Dahal P, Shrestha ML, Panthi J, et al. Modeling the future impacts of climate change on water availability in the Karnali River Basin of Nepal Himalaya. Environ. Res. 2020; 109430.

Dahe Q, Shiyin L, Li Peiji. Snow Cover Distribution , Variability , and Response to Climate Change in. J. Clim. 2006; 19: 1820–1833.

Dandekhya S, England M, Ghate R, et al. The Gandaki Basin. 2017

De Freitas GN. São Paulo drought: trends in stream flow and their relationship to climate and human-induced change in Cantareira watershed, Southeast Brazil. Hydrol. Res. 2020; 750–767.

Ding J, Chen L, Ji C, et al . permafrost regions 2017; 1–6.

Dobrowski SZ, Abatzoglou JT, Greenberg JA, et al. How much influence does landscape-scale physiography have on air temperature in a mountain environment? Agric. For. Meteorol. 2009; 149: 1751–1758.

Fujita K, Ageta Y. Effect of summer accumulation on glacier mass balance on the Tibetan Plateau revealed by mass-balance model. J. Glaciol. 2000; 46: 244–252.

Gardner AS, Moholdt G, Cogley JG, et al . A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science (80-.). 2013; 340: 852–857.

Gascoin S, Kinnard C, Ponce R, et al. Glacier contribution to streamflow in two headwaters of the Huasco River, Dry Andes of Chile. Cryosphere 2011; 5: 1099–1113.

Gascoin S, Lhermitte S, Kinnard C, et al. Wind effects on snow cover in Pascua-Lama , Dry Andes of Chile. Adv. Water Resour. 2013; 55: 25–39.

Ghimire, N. Engineering Geological Site Characterization for Large Dam of Budhi Gandaki Hydropower Project in Nepal. American Geophysical Union, Fall Meeting 2018

Giese E, Mossig I, Rybski D, et al. Long term analysis of air temperature trends in central Asia. Erdkunde 2007; 186–202.

Gobiet A, Kotlarski S, Beniston M, et al. 21st century climate change in the European Alps-A review. Sci. Total Environ. 2014; 493: 1138–1151.

Gurung DR, Giriraj A, Aung KS, et al. Snow-Cover Mapping and Monitoring in the Hindu Kush-Himalayas. Int. Cent. Integr. Mt. Dev. 2011; 1–44.

Haeberli W, Colin W. Snow and Ice-Related Hazards , Risks , and Disasters : A General Framework. 2017.

Hall DK, Riggs GA, Digirolamo NE, et al. Evaluation of MODIS and VIIRS cloud-gap-filled snow-cover products for production of an Earth science data record. Hydrol. Earth Syst. Sci. 2019; 5227–5241.

Hall DK, Riggs GA, Foster JL, et al. Development and evaluation of a cloud-gap- filled MODIS daily snow-cover product. Remote Sens. Environ. 2010; 114: 496–503.

Hewitt K. The Karakoram anomaly? Glacier expantion and the “Elevation effect,” Karakoram Himalaya. Mt. Res. Dev. 2005; 25: 332–340.

Heynen M, Miles E, Ragettli S, et al. Air temperature variability in a high-elevation Himalayan catchment. Ann. Glaciol. 2016; 57: 212–222.

Hood E, Williams M, Cline D. Sublimation from a seasonal snowpack at a continental , mid-latitude alpine site. Hydrol. Process. 1999; 1797: 1781–1797.

Immerzeel WW. Climate Change Will Affect the Asian Water Towers. Science (80-.). 2010; 1382: 328.

Jain SK, Goswami A, Saraf AK. Role of elevation and aspect in snow distribution in Western Himalaya. Water Resour. Manag. 2009; 23: 71–83.

Kaini S, Nepal S, Pradhananga S, et al. Impacts of climate change on the flow of the transboundary Koshi River, with implications for local irrigation. Int. J. Water Resour. Dev. 2020; 00: 1–26.

Kattelmann R. WATER RESOURCES UNCERTAINTY IN ASSESSING HIMALAYAN. Mt. Res. Dev. 1987; 7: 279–286.

Kendall MG. Rank correlation measures. London: Charles Griffin; 1975.

Kendall MG, Gibbons JD. Rank correlation methods. London: Edward Arnold; 1990

Khadka M, Kayastha RB, Kayastha R. Future projection of cryospheric and hydrologic regimes in Koshi River basin, Central Himalaya, using coupled glacier dynamics and glacio-hydrological models. J. Glaciol. 2020; 66: 831–845.

Khatiwada KR . Karnali River Basin 2016; 1–11.

Khatiwada KR, Panthi J, Shrestha ML. Hydro-Climatic Variability in the Karnali River Basin 2016; 1–14.

Klein AG, Barnett AC. Validation of daily MODIS snow cover maps of the Upper Rio Grande River Basin for the 2000 – 2001 snow year 2003; 86: 162–176.

Kotlarski S, Bosshard T, Lüthi D, et al. Elevation gradients of European climate change in the regional climate model COSMO-CLM. Clim. Change 2012; 112: 189–215.

Li C, Su F, Yang D, et al. Spatiotemporal variation of snow cover over the Tibetan Plateau based on MODIS snow product , 2001 – 2014. Int. J. Climatol. 2017.

Li L, Zou Y, Li Y, et al. Trends , change points and spatial variability in extreme precipitation events from 1961 to 2017 in China. Hydrol. Res. 2020; 484–504.

Li X, Williams MW. Snowmelt runoff modelling in an arid mountain watershed , Tarim Basin , China. Hydrol. Process. 2008; 3940: 3931–3940.

Liniger HP, Weingartner R, Grosjean M, Mountains of the World: Water Towers for the 21st Century. A Contribution to Global Freshwater Management, Mt. Agenda, Dep. of Geogr., Univ. of Berne, Berne. 1998

Liu X, Cheng Z, Yan L, et al. Elevation dependency of recent and future minimum surface air temperature trends in the Tibetan Plateau and its surroundings. Glob. Planet. Change 2009; 68: 164–174.

Lutz AF, Immerzeel WW, Shrestha AB, et al. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nat. Clim. Chang. 2014; 4: 587–592.

Mann HB. Nonparametric tests against trend. Econometrica 1945;13:245–59.

Magnusson J, Jonas T, Löpez-Moreno I, et al. Snow cover response to climate change in a high alpine and haif-glacierized basin in Switzerland. Hydrol. Res. 2010; 41: 230–240.

Marty C, Tilg AM, Jonas T. Recent evidence of large-scale receding snow water equivalents in the European alps. J. Hydrometeorol. 2017; 18: 1021–1031.

Masiokas MH, Villalba R, Luckman BH, et al. Snowpack Variations in the Central Andes of Argentina and Chile, 1951–2005: Large-Scale Atmospheric Influences and Implications for Water Resources in the Region. J. Clim. 2006; 6334–6352.

Mayer C, Lambrecht A, Oerter H, et al. Accumulation Studies at a High Elevation Glacier Site in Central Karakoram. Adv. Meteorol. 2014.

Meehl GA, Stocker TF. Global Climate Projections. IPCC. 2007.

Meetei PN, Ahluwalia RS, Rai SP, et al. Spatio-temporal analysis of snow cover and effect of terrain attributes in the Upper Ganga River Basin, central Himalaya. Geocarto Int. 2020; 0: 1–21.

Meybeck M, Green P, Vorosmarty CJ. Comments A New Typology for Moun- tains and Other Relief Classes : An Application to Global Continental Water Resources and Distribution Population Indicators Development for Mountain Regions. Mt. views 2001; 21: 21–22.

Mote PW. Climate-Driven Variability and Trends in Mountain Snowpack in Western North America *. J. Clim. 2006; 6209–6220.

Muhammad S, Thapa A. An improved Terra – Aqua MODIS snow cover and Randolph Glacier Inventory 6 . 0 combined product (MOYDGL06 *) for high-mountain Asia between 2002 and 2018. Earth Syst. Sci. Data 2020; 12: 345–356.

Nepal S, Shrestha AB. Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature. Int. J. Water Resour. Dev. 2015; 31: 201–218.

Nepal S. Impacts of climate change on the hydrological regime of the Koshi river basin in the Himalayan region. J. Hydro-Environment Res. 2016; 10: 76–89.

Nepal S, Krause P, Flügel WA, et al. Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model. Hydrol. Process. 2014; 28: 1329–1344.

Nepal S, Pradhananga S, Bajracharya A. Water balance assessment of the Gandaki river basin by applying the J2000 hydrological model. ICIMOD 2017; 1–10.

Nepal S, Shrestha AB. Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature. Int. J. Water Resour. Dev. 2015; 31: 201–218.

Neupane RP, Yao J, White JD. Estimating the effects of climate change on the intensification of monsoonal-driven stream discharge in a Himalayan watershed. Hydrol. Process. 2014; 6250: 6236–6250.

Pandey VP, Dhaubanjar S, Bharati L, et al. Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: Hydrological model development using multi-site calibration approach (Part-A). J. Hydrol. Reg. Stud. 2020; 29: 100690.

Parajka J, Blöschl G. Validation of MODIS snow cover images over Austria. Hydrol. Earth Syst. Sci 2006; 10: 679–689.

Pepin N, Bradley RS, Diaz HF, et al. Elevation-dependent warming in mountain regions of the world. Nat. Clim. Chang. 2015; 5: 424–430.

Pepin NC, Lundquist JD. Temperature trends at high elevations : Patterns across the globe. Geophys. Res. Lett. 2008; 35: 1–6.

Pomeroy, JW, Gray, DM Snowcover: Accumulation, Relocation, and Management. National Hydrology Research Insti- tute, Saskatoon, Canada, NHRI Science Report 1995; 7, Saskatoon

Pradhananga NS, Kayastha RB, Bhattarai BC, et al. Estimation of discharge from Langtang River basin , Rasuwa , Nepal , using a glacio-hydrological model. Ann. Glaciol. 2014; 55: 223–230.

Prakash S, Singh D, Jacob N, et al. Identifying contribution of snowmelt and glacier melt to the Bhagirathi River (Upper Ganga) near snout of the Gangotri Glacier using environmental isotopes. Catena 2019; 173: 339–351.

Pu Z, Xu L, Salomonson V V. MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau. 2007; Geophys. Res. Lett. 34.

Qin J, Yang K, Liang S, et al. The altitudinal dependence of recent rapid warming over the Tibetan Plateau. Clim. Change 2009; 321–327.

Rasul G. Ecosystem services and agricultural land-use practices: A case study of the Chittagong Hill Tracts of Bangladesh. Sustain. 2009; Sci. Pract. Policy 5: 15–27.

Rodell M, Houser P, Jambor U, et al. THE GLOBAL LAND DATA ASSIMILATION SYSTEM. Am. Meteorol. Soc. 2004; 85: 381–394.

Rodgers JL, Nicewander WA. Thirteen ways to look at the correlation coefficient. Am Stat 1988;42:59–66.

Sadoff C, Nagaraja RH. Ganges Strategic Basin Assessment A Discussion of Regional Opportunities and Risks. World Bank South Asia Reg. Rep. 2014.

Saloranta T, Thapa A, Kirkham JD, et al. A model setup for mapping snow conditions in high-mountain himalaya. Front. Earth Sci. 2019; 7: 1–18.

Sharma, CK. A Treatise on Water Resources of Nepal. MASS Printing Press, Kathmandu, Nepal, 1997.

Sharma C, Ojha C SP. Detection of Changes in Temperature in Upper Ganga River Basin EP53F-1961. 2018; p. 10500106.

Sharma KP, Iii BM, Vorosmarty CJ. Anthropogenic, climatic, and hydrologic trends in the kosi basin, himalaya. Clim. Change 2000; 47: 141–165.

Shiwakoti S. Hydrological Modeling and Climate Change Impact Assessment Using HBV Light Model : A Case Study of Karnali River Basin 2012; 1–19.

Shrestha M, Koike T, Hirabayashi Y, et al. Integrated simulation of snow and glacier melt in water and energy balance-based, distributed hydrological modeling framework at Hunza River Basin of Pakistan Karakoram region. J. Geophys. Res. Atmos. 2015; 4889–4919.

Shrestha R. Koshi River Basin Inventory , Nepal Submitted to : Prof . Dr . Lars Ribbe , CUAS / ITT 2019

Shrestha ML. Interannual variation of summer monsoon rainfall over Nepal and its relation to Southern Oscillation Index. Meteorol. Atmos. Phys. 2000; 75: 21–28.

Siderius C, Biemans H, Wiltshire A, et al. Snowmelt contributions to discharge of the Ganges. Sci. Total Environ. 2013; 468–469: S93–S101.

skhdmp.gov.np-2021

Smith T, Bookhagen B, Rheinwalt A. Spatiotemporal patterns of High Mountain Asia’s snowmelt season identified with an automated snowmelt detection algorithm, 1987-2016. Cryosphere 2017; 11: 2329–2343.

Spearman C. The proof and measurement of association between two things. Am J Psychol 1904;15:72–101.

Stigter EE, Litt M, Steiner JF, et al. The Importance of Snow Sublimation on a Himalayan Glacier 6: 1–16.

Strasser U, Bernhardt M, Weber M, et al 2008. The Cryosphere Is snow sublimation important in the alpine water balance ? Cryosph. 2018; 53–66.

Tahir AA, Chevallier P, Arnaud Y, et al. Snow cover trend and hydrological characteristics of the Astore River basin (Western Himalayas) and its comparison to the Hunza basin (Karakoram region). Sci. Total Environ. 2015; 505: 748–761.

Tahir AA, Chevallier P, Arnaud Y, et al. Snow cover dynamics and hydrological regime of the Hunza River basin , Karakoram Range , Northern Pakistan. Hydrol. Earth Syst. Sci. 2011; 2275–2290.

Tendolkar R, Venkataraman A, Blaha D, et al. Cumulative Impact Assessment and Management (CIA): Hydropower Development in the Trishuli River Basin 2020.

Thapa BB, Pradhan BB. Water Resources Development: Nepalese Perspective. Institute for Integrated Development Studies, Kathmandu, Nepal, 1995.

Thanju RP. Kali Gandaki ‘A’ Hydroelectric Project in Environmental Perspectives. Hydro Nepal J. Water, Energy Environ. 2008; 1: 15–21.

Thayyen R, Gergan JT. Role of glaciers in watershed hydrology : a preliminary study of a “ Himalayan catchment .” Cryosph. 2010

Viste E, Sorteberg A. Snowfall in the Himalayas : an uncertain future from a little-known past 2015; 1147–1167.

Viviroli D, Dürr HH, Messerli B, et al. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resour. Res. 2007; 43: 1–13.

Viviroli D, Weingartner R. The hydrological significance of mountains: from regional to global scale. Hydrol. Earth Syst. Sci. 2004; 8: 1017–1030.

Wijngaard R, Lutz AF, Khanal S. Future changes in hydro-climatic extremes in the Upper Indus , Ganges , and Brahmaputra River basins 2017; 1–26.

Yadav BC, Thayyen RJ, Jain K. Topoclimatic zones and characteristics of the upper Ganga basin, Uttarakhand, India. Int. J. Climatol. 2020; 40: 6002–6019.

Yang J, Jiang L, Ménard CB, et al. Evaluation of snow products over the Tibetan Plateau. Hydrol. Process. 2015; 29: 3247–3260.

Yu J, Zhang G, Yao T, et al. Developing Daily Cloud-Free Snow Composite Products From MODIS Terra – Aqua and IMS for the Tibetan Plateau. IEEE Trans. Geosci. Remote Sens. 2015; 1–10.

Zhou J, Pomeroy JW, Zhang W, et al. Simulating cold regions hydrological processes using a modular model in the west of China. J. Hydrol. 2014; 509: 13–24.