Chapter 4: Monitoring and assessment of glaciers and high-altitude lakes of the Manas-Beki basin

4.1 Introduction

The environment of the third pole is changing rapidly altering the delicate balance between the cryosphere and the hydrosphere [1, 2]. Visible changes in the cryosphere are one of the best indicators of climate change [3] and analysis of the changes in glaciers, glacial and high-altitude lakes is necessary to understand the hydrological response of a glaciated basin to observed changes [4]. This chapter uses geospatial data to estimate the changes in the glacier and lake regimes of the Manas-Beki river basin. The following aspects are studied within this objective:

i. Estimation of glaciers, glacial and high-altitude lakes during 2020 and their distribution in the Manas-Beki basin
ii. Analysis of changes in glaciers, glacial and high-altitude lakes from 1990 to 2020 in the Manas-Beki basin
iii. Analysis of available gridded climate data including temperature and precipitation for the basin

Climate change is affecting the high mountain regions all over the world and the Himalayan region, which stores about 12,000 km^3 of fresh water in around 15,000 glaciers sustaining an estimated 10% of the world's population, is one of the most important regions for climate change research [5, 6, 7]. The effects of global environmental change on the Himalayas are manifested through a rise in temperature, changes in precipitation trends, retreat and loss of glaciers, permafrost degradation, vegetation changes, decrease in snow cover area, and increase in surface water bodies [5, 8, 9, 10]. The annual mean surface air temperature of the Hindu Kush Himalayas is observed to have increased at a rate of 0.1°C/decade between 1901 and 2014 while the trend is higher during 1951-2014 (~0.2°C/decade) and is even higher at higher altitudes (>4000 m) where it is observed to be increasing by around 0.5°C/decade [9]. The observed rate of warming in the Himalayan region is higher than the global warming rate making the region highly sensitive to climate change [11]. A significant increase in precipitation is reported for the Hindu Kush Himalayan region with an increase rate of around 5.28% per decade for precipitation trends observed between 1961 to 2013 [12]. On the other hand, snowfall is decreasing over the Himalayas and is estimated to decrease with rising temperatures [13]. The response of the Himalayan landscape to climate change is demonstrated by evident changes in land cover in the higher altitudes, primarily including a decrease in snow and ice cover areas and an increase in water bodies and vegetation [10].

The cryosphere, including glaciers, snow, and permafrost is highly sensitive to slight variations in the climate interacting and responding in different ways [14]. A river's overall stream runoff is largely influenced by glaciers, snowmelt, and precipitation, and modifications to any of these factors can have a substantial impact on the hydrological regime of the river [15, 16, 17]. The rivers originating in the Himalayas are largely snow and glacier-fed and hence changes in the cryosphere can have major implications on the freshwater availability in the highly populated downstream regions [1, 18] as well as lead to increased disasters such as floods, which can jeopardize water systems endangering downstream agriculture and infrastructure [19, 20]. The contribution of rainfall, snow melt, and glacier melt to the stream runoff was estimated for the major rivers of the Hindu Kush Himalayas and it was observed that even though monsoon rainfall has the highest contribution to runoff during June-September in the Brahmaputra basin, snow and glacier melt is relatively important, making up around 20-23% and 12% of the annual flow respectively [21].

A better understanding of changes in the cryosphere and the underlying causes of change can be instrumental in reducing the risk of hazards in high-altitude areas [22]. Most of the Himalayan glaciers are shrinking with an estimated loss of around 13% of the glacier area in the last few decades which will be leading to changes in the seasonality of water runoff and modifying the risks associated with natural hazards [23, 24]. An estimated loss of around 11% in the glacier area was reported for the Himalayan region between 1990 and 2015 with the highest loss during 2010-2015 [25]. Similarly, glacier mass loss has been reported from all the sub-regions in the Himalayan landscape and the rate of loss is estimated to have almost doubled between 2000-2016 in comparison to the loss during 1975-2000 [26]. Several researchers have suggested that clean ice glaciers and glaciers with pro-glacial lakes are more sensitive to observed climate change than debris-covered glaciers [27-30]. Glacier size, elevation, and aspect are also important factors, and small glaciers at lower altitudes are reported to be most vulnerable to climate change [25, 28, 31].

Apart from glaciers, the Himalayan region is scattered with numerous lakes at high elevations that support diverse ecosystems. These high-altitude lakes in the Himalayan landscape are sustained through two different means - some are fed by the melting of glaciers (known as pro-glacial and supra-glacial lakes) while others are formed from depressions that accumulate rainwater or melting permafrost [32, 33]. Understanding the physical response of lakes, particularly changes in glacial lakes, is crucial in comprehending the impact of climate change on high-altitude basins worldwide [34, 35]. Various studies observed varied changes related to lakes in different parts of the Himalayan region including an increase in the glacial lake area, a decrease in the area of non-glacial lakes, the formation of new lakes, and the disappearance of lakes [36-39]. In the Central Tibetan Plateau, 150 new lakes formed between 1972-2009 with a 173% increase in glacial lake area [40]. In the Central Himalayas, an increase in around 57% of lakes connected to glacier recession is observed between 1994 and 2017 [41]. The Central and Eastern Himalayan region was observed to have higher rates of change in glacial lakes compared to the rest of the Himalayan region [42]. Glacier-fed lakes and small lakes are more sensitive to climate change and the largest change was observed at higher altitudes (>5000 m) [43, 44, 45]. Increased glacial melt resulting in the rapid expansion of associated lakes can result in the occurrence of Glacier Lake Outburst Floods (GLOFs) that pose a serious risk for catastrophic damages to infrastructure and fatalities in downstream regions [46-50].

Remote sensing data has been widely used to observe the changes in glaciers and associated lakes in high-altitude regions as a response to climate change [32, 51, 52, 53]. Insufficient climate-related data is available for the Himalayas, emphasizing the necessity for coordinated transboundary research to work collaboratively on the impacts of climate change on the cryosphere [23]. Despite the fact that research on glaciers and glacial lakes in the Himalayan region has been conducted extensively in relation to climate change, there is a scarcity of detailed observations at the basin level in the Eastern Himalayas. The Eastern Himalayas is warming consistently with an annual increase of ~0.03°C/year though precipitation trends do not show any specific trend [54, 55]. Most of the studies concentrated on Eastern Himalayas were on glacier and glacial lake change assessment for Sikkim or Arunachal Himalayas [56-62] with emphasis on rapidly expanding lakes as this region is categorized as a high-risk zone for the occurrence of GLOFs [63, 64]. The scarce availability of cloud-free satellite data for the Eastern Himalayas coupled with difficult and inaccessible terrain makes the region challenging for researchers to carry out field validation [57, 65, 66]. This chapter characterizes and analyzes the changes in the glaciers and glacial lakes in the Manas-Beki river basin from 1990 and 2020. Several studies have been carried out for glacier and glacial lake identification in the Bhutan Himalayas at a regional scale but a comprehensive study at the basin scale to understand the drainage basin response due to changes is lacking [67-72].

4.2 Data and methods

4.2.1 Data and resources used

Satellite data from different sources were used to identify glaciers and high-altitude lakes in the Manas-Beki river basin. Landsat satellite data for 1990 and 2020 for the four glaciated sub-basins: Mangde Chu, Chamkar Chu, Kuri Chu, and Dangme Chu for the month of December were obtained from NASA's USGS portal for extraction of glacier extents to maintain the same period for comparison and obtain the maximum area of glaciers after seasonal accumulation. Landsat TM and OLI satellite data for the same years (1990 and 2020) for the month of September were used to extract lake extent as lakes are mostly unfrozen during this time after glacier ablation is over. A total of 4 scenes was required to generate the composite of the entire study area including the four glaciated sub-basins. Sentinel-2 MSI satellite data of 10 m spatial resolution was used to manually check and modify the extracted glacier and lake extents for the year 2020. The GEE cloud-computing platform was used to download the cloud-free composites of the four glaciated sub-basins for Nov/Dec 2020 as the period is relatively cloud-free. ASTER DEM of 30 m resolution was used to calculate the elevation, slope, and aspect. Erdas Imagine software was used for classification and post-classification analysis and ArcGIS software was used for mapping and statistical analysis. GEE was also used to download the monthly mean of air temperature at 2 m above land and precipitation data including rain and snow from 1990 to 2020 from European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global atmospheric reanalysis model data within the study area to have a view of the climate change scenario [73]. To aid in identifying glaciers and glacial lakes, available glacier database sourced from GLIMS (Global Land Ice Measurements from Space) and Glacial Lake Inventory (GLI) obtained from JAXA (Japan Aerospace Exploration Agency) was also acquired [74, 75]. The details of the datasets used for the study are given in Table 4.1.

Table 4.1 Details of satellite data used for analysis of glacier and high-altitude lakes in Manas-Beki basin

Satellite/ sensors	Spatial resolution	Time of acquisition	Path	Row	No. of scenes	Source
Landsat TM	30 m	Sep & Dec 1990	137	40-41	4	USGS
Landsat TM	30 m	Sep & Dec 1990	138	40-41	4	USGS
Landsat OLI	30 m	Sep & Dec 2020	137	40-41	4	USGS
Landsat OLI	30 m	Sep & Dec 2020	138	40-41	4	USGS
Sentinel-2 MSI	10 m	Nov/Dec 2020	-	-	-	GEE

ASTER DEM	30 m	October 2011	-	-	-	NASA
GLIMS glacier database	-	2018	-	-	-	NSIDC
Glacial lakes database	-	2012	-	-	-	JAXA
ERA5 Reanalysis	0.1^0 x 0.1^0	1990-2020	-	-	-	ECMWF

4.2.2 Methodology

Before the extraction of features, the raw satellite images (Landsat) were subjected to pre-processing steps. Since satellite data is available in individual band data for each wavelength band imaged, the individual bands were composited into a single stacked image, and images were radiometrically corrected to improve feature extraction. The Landsat images used for 1990 and 2020 were the orthorectified reflectance product and perfectly aligned with each other as geometric correction was already taken care of by the data provider with high accuracy. The Autosync module in Erdas Imagine 2011 software was utilized to calibrate Sentinel images with Landsat images and ensure they perfectly coincided with each other to enable image comparison for change analysis. The resulting average overall calibration error for Sentinel data was estimated to be around 0.5 (±0.2) pixels. A combination of automated and manual methods has been used to delineate the glacier and glacial boundaries which are detailed in the following subsections. Figure 4.1 gives an overview of the overall methodology used to develop the outputs for this objective.

Glacier delineation

For the identification of snow and ice from satellite images, the SWIR and NIR bands have been widely used due to the distinct differences in spectral characteristics at these wavelength regions [76, 77, 78]. The snow and ice cover regions extracted in the previous chapter for 1990 and 2020 using Landsat TM and OLI respectively for the basins were used to identify glacier regions with a combination of slopes derived from ASTER DEM [79]. Glacier extents were manually delimited using visual interpretation method from higher resolution Sentinel-2 data (10/20 m resolution) for 2020, as the automatic detection of glacier boundaries can be challenging due to the presence of debris especially around the glacier snout which is common in the Himalayas making it hard to differentiate from the surrounding lateral and end moraines [57]. Manual delimitation from Sentinel-2 data enabled the identification of debris cover as well as small glaciers not easily identifiable in Landsat images. False Colour Composite of the

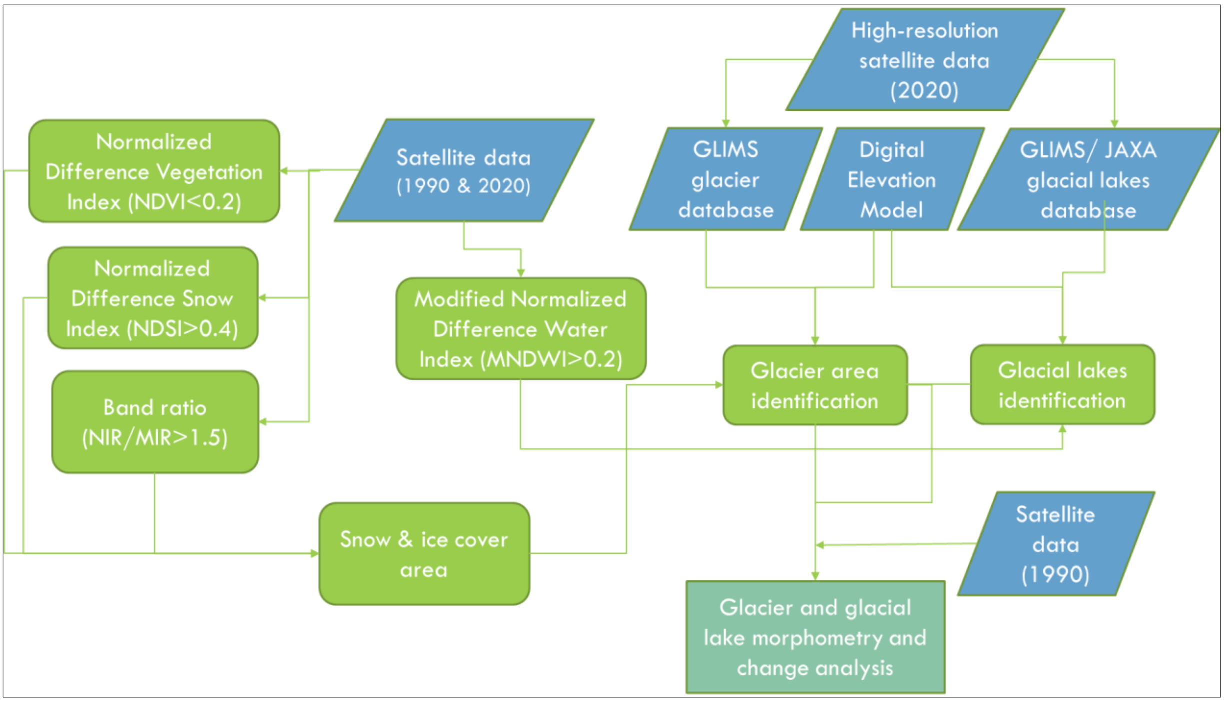


Figure 4.1 Flowchart of overall methodology used for mapping and change analysis of glaciers and high-altitude lakes in Manas-Beki basin

Red, NIR, and SWIR bands was used for manual delimitation of glaciers boundaries with the aid of distinctive glacier surface features identifiable in corresponding bands 4, 8, and 11 of the Sentinel-2 MSI sensor [80, 81]. Glaciers were detected using higher-resolution Sentinel-2 data from 2020 and an evaluation of changes between 1990 and 2020 was done by comparison with Landsat TM images. The glacier outlines from the GLIMS glacier database were also used for reference while identifying the glaciers. The ASTER DEM was used to extract information related to elevation, slope, and aspect of the identified glaciers.

Glacial lake delineation

Lakes with open surface water can be easily identified from satellite images due to their distinct spectral characteristics using suitable spectral band indices [82, 83]. The high-altitude lakes (at altitudes >3500 m) were extracted by using a spectral index on satellite images along with slopes derived from DEM. To accentuate the open water features from multi-spectral satellite images, the Modified Normalized Difference Water Index (MNDWI) was first estimated from Landsat data of 2020, leveraging the information from the Green (G) and Shortwave Infrared (SWIR) bands [84]. The formula for calculating MNDWI is given as:

$$MNDWI = \frac{G - SWIR}{G + SWIR}$$

For Landsat OLI data, Band 3 and Band 6 were used to generate MNDWI, and the output image was used to extract surface water features which are denoted by higher positive values whereas other surrounding features like soil and vegetation are indicated by lower negative values. A threshold of 0 is generally used for extracting water bodies from MNDWI images but the value can be adjusted to achieve better results [83, 84]. All positive values above 0 were used to extract the lake areas from the satellite images but snow and ice cover areas along with areas under shadow were also extracted along with water bodies. The snow and ice cover areas extracted for snow and glacier mapping previously were used to eliminate the snow and ice cover areas from the images. Areas with slopes less than 10% derived from DEM were retained to eliminate the shadow areas which were primarily due to the high mountain topography of the region. The final lake boundaries were delimited by manual corrections for errors due to the presence of clouds and shadows using Sentinel-2 data. Some of the smaller-sized and completely frozen lakes next to glaciers were visually interpreted due to ambiguities in automatic extraction. The glacial lake database from JAXA was also used as a reference while identifying the high-altitude lakes. An inventory of high-altitude lakes was developed for all the glaciated sub-basins for 2020 by extracting the relevant attributes related to altitude from the ASTER DEM for each identified lake which were then was overlaid on the Landsat TM image of 1990 to manually extract the change in surface area.

Change analysis

The percentage change in glacier and high-altitude lake areas during the 30 years of analysis has been estimated using the formula:

$$\text{Percentage change} = \frac{A_{2020} - A_{1990}}{A_{1990}} \times 100$$

Where, A_{2020} and A_{1990} are the areas assessed during the years 2020 and 1990 respectively.

Error estimates

The accuracy of mapping glaciers and glacial lakes using satellite images is influenced by two factors: the resolution of the data set in terms of pixel size, and the accuracy of referencing the data set to a reference system [85]. We have not considered the error due to referencing in this study as the value is very small in comparison to the resolution error and can be neglected. The resolution error for the mapping is estimated from the number of pixels along the extracted boundary of the glacier or lake and the spatial resolution using the formula given by Basnett *et al* for calculating mapping uncertainty [86].

$$Mapping\ Uncertainty = N \times \frac{A}{2}$$

Where, N is the number of pixels along the glacier or lake boundary and A is the area of the pixel.

Gridded climate data analysis

ECMWF ERA5 reanalysis data for the study area was used to analyze the trends in monthly average air temperature and precipitation including rainfall and snowfall from 1990 to 2020 for each of the glaciated sub-basins. The Himalayan region has limited data from in-situ or satellite observations; therefore, numerous studies have relied on ERA5 reanalysis data to gain insight into the climate change trends over the past several years [37, 87-89]. When compared to the range of other available datasets, the reanalysis data has been deemed highly suitable for environmental analysis in data-scarce regions such as the Himalayas [90]. Monthly average mean of air temperature above 2m from the surface, and total precipitation including rainfall and accumulated snowfall were extracted for each of the sub-basin using GEE. Data were extracted for the four sub-basins: Mangde Chu, Chamkar Chu, Kuri Chu and Dangme Chu in a GIS environment and analyzed using Microsoft Excel for possible trends.

4.3 Results

4.3.1 Glaciers and their changes

Glacier distribution, area and size

Glacier extents were extracted for 2020 for all four glaciated sub-basins of Manas-Beki river basin and changes were analyzed by comparison with glacier extents extracted for 1990 to observe the changes in glaciers in the basin over the span of 30 years. Figure 4.2 shows the distribution of glaciers identified in the year 2020. Two types of glaciers were observed in the study area: clean-ice and debris-covered glaciers (Figure 4.3). Debris-covered glaciers comprise only about 2% of the total glaciers identified in 2020.

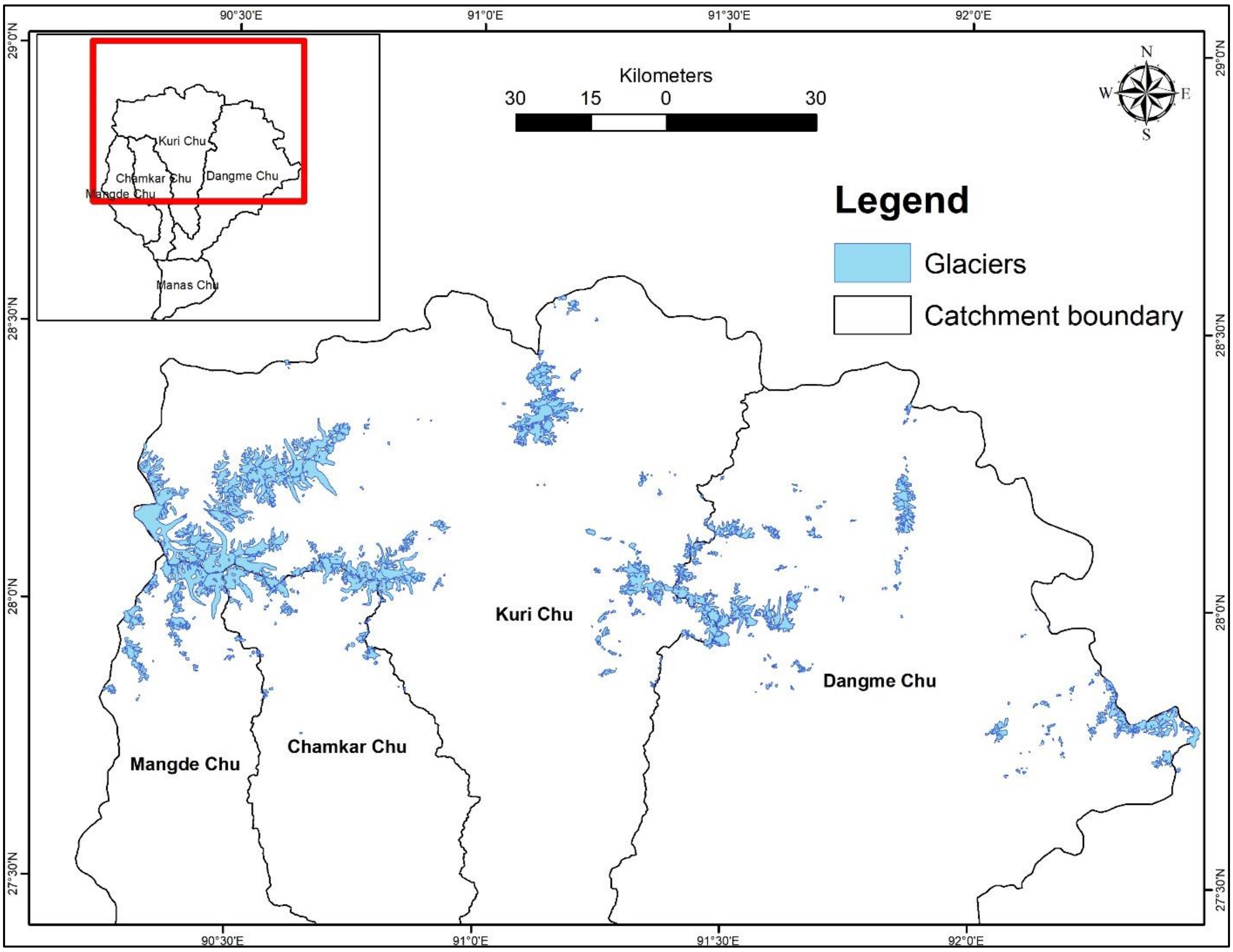


Figure 4.2 Distribution of glaciers in upper catchment of Manas-Beki river basin based on satellite data of 2020

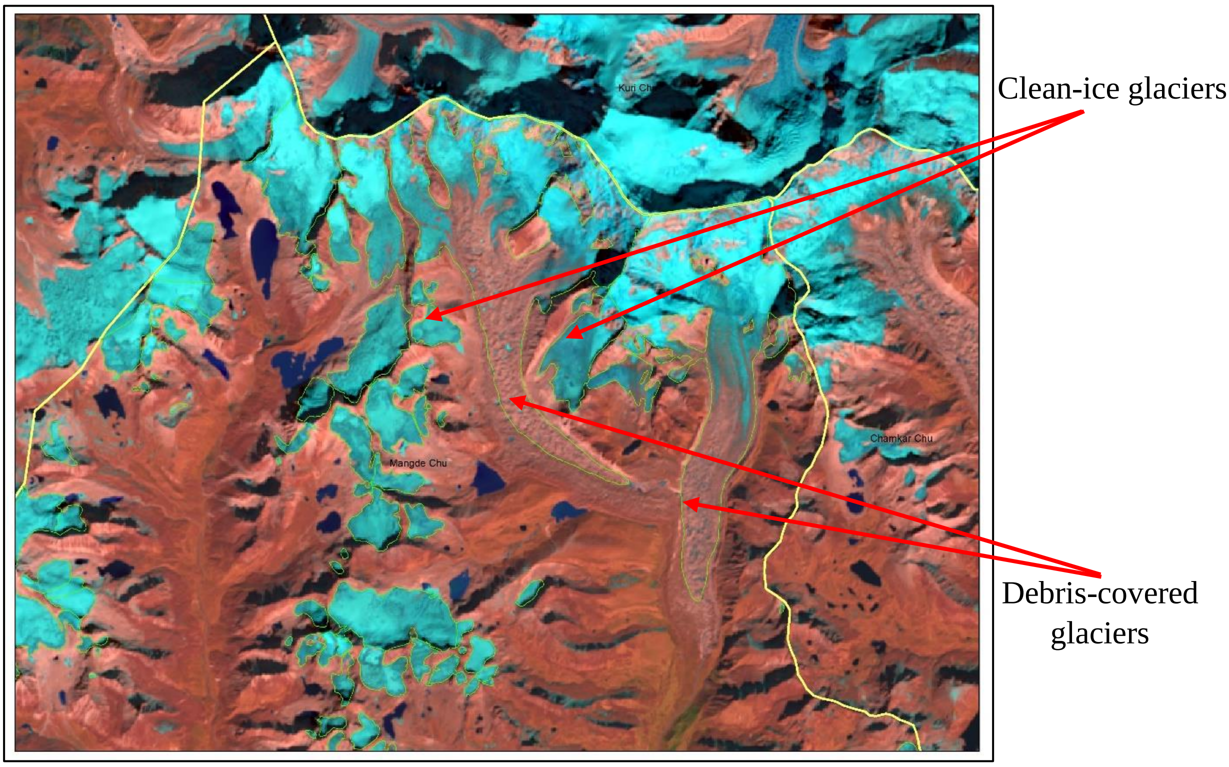


Figure 4.3 Types of glaciers in the Manas-Beki basin

In 2020, around 1241 glaciers were identified which occupied nearly 10.4% of the total area of the four glaciated sub-basins in Manas-Beki river basin. This has decreased from around 11.5% glacier coverage observed in 1990. Glacier area has decreased from 3264.9 (±20.1) km^2 in 1990 to 2961.6 (±5.8) km^2 in 2020. The Kuri Chu sub-basin has the highest percentage of glacier coverage (~5.9%) followed by Mangde Chu (~2.6%), Chamkar Chu (~1.9%), and the least in Dangme Chu (~1.8%) observed during 2020. Figure 4.4 shows the change in total glacier coverage area and number of glaciers in the four sub-basins. It is observed that though the glacier area has decreased, the number of glaciers has increased between 1990 and 2020. The glacier coverage area has drastically reduced in all the sub-basins between the observation period of 30 years between 1990 to 2020 with the highest percentage change observed in count as well as area in the Dangme Chu basin (17% and 38% respectively) (Figure 4.5).

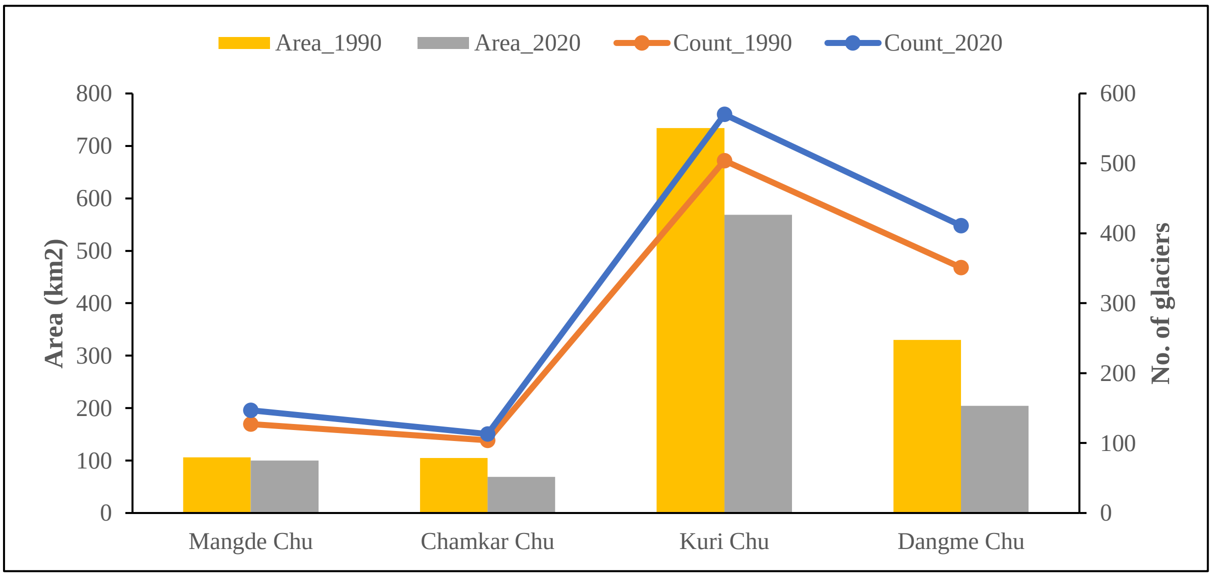


Figure 4.4 Changes in glacier count and area in sub-basins of Manas-Beki river (1990-2020)

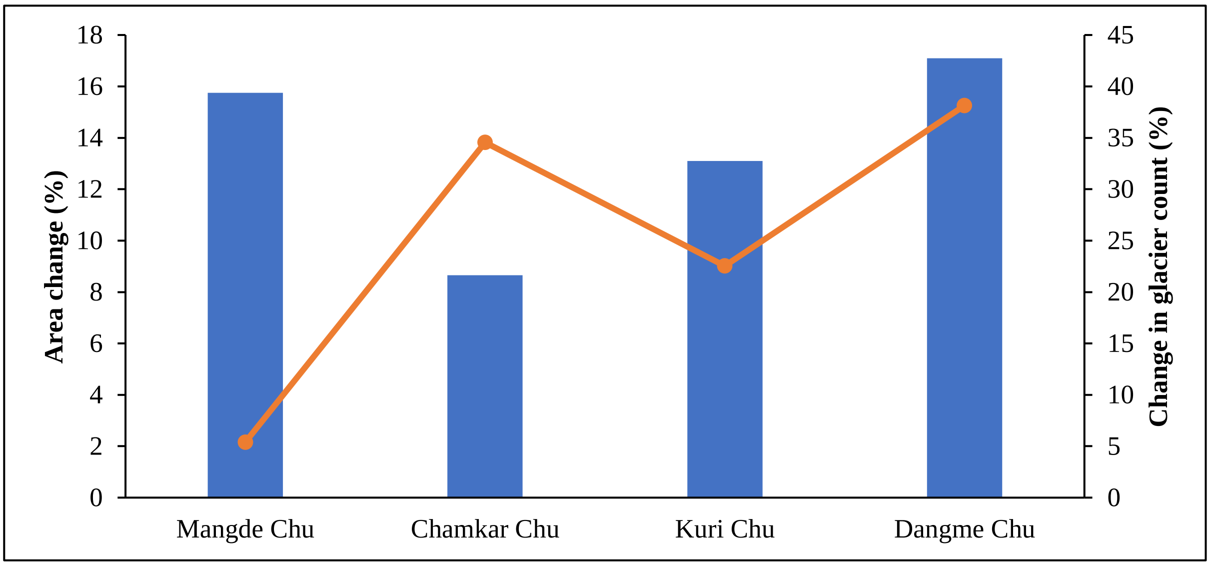


Figure 4.5 Percentage change in glacier count and area in sub-basins of Manas-Beki river (1990-2020)

Three different types of changes are observed in the study area; some of the glaciers have totally disappeared between 1990 and 2020, some have reduced in size and some have fragmented into two or more smaller glaciers. Figure 4.6 and Table 4.2 shows the types of changes in glaciers between 1990-2020 in the study area. It is observed that around 42 glaciers have totally disappeared covering a total area of around 11.25 km^2 during the period 1990-2020. Out of the total 1086 glaciers in 1990, 993 glaciers have reduced in size while 108 have fragmented into smaller glaciers resulting in an increase in the count of glaciers in 2020. The highest disappearance and fragmentation in glaciers is seen in the easternmost Dangme Chu sub-basin whereas, the highest number of glaciers reduced in size is observed in Kuri Chu sub-basin.

The size of glaciers in Manas-Beki river basin ranged from 0.02 (±0.007) km^2 to 60.0 (±1.5) km^2 in 1990 which has changed to 0.004 (±0.001) km^2 to 51.6 (±0.6) km^2 in 2020. The glaciers are categorized based on their sizes as small (< 0.5 km^2), medium (0.5 – 1 km^2), large (1 – 5 km^2), and very large (> 5 km^2) glacier sizes [91]. It is observed that the highest frequency of glaciers is of the small size (<0.5 km^2) but it occupies a lesser coverage area. In 2020, small-size glaciers have increased in number whereas medium, large, and very large ones have decreased. Figure 4.7 shows the area occupied (in bars) by glaciers in 1990 and 2020 as well as the frequency of glaciers (in lines) in different categories of glacier sizes for the four sub-basins of Manas-Beki river. As the total area of glacier cover is concerned, the highest decrease is due to the very large size glaciers (>5 km^2). The statistics indicate that though maximum area change in glaciers is due to changes in the very large-sized glaciers as these occupy larger areas, the number of glaciers that have totally disappeared or altered drastically is higher in small and medium-sized glaciers. The trend of change remains almost the same in all four sub-basins.

The percentage change in glacier coverage area based on different glacier sizes is shown in Figure 4.8. It is observed that the highest change in glacier area is loss of area due to the medium-sized glaciers (~48.6%) where the maximum change is in the Chamkar Chu sub-basin, followed by the very large size glaciers (~35.9%) where the maximum change is in the Dangme Chu basin. An overall increase in area is observed for the small-size glaciers in the basin except in the Dangme Chu basin where a loss of area is observed. All other glacier sizes show area loss except the medium-sized glaciers in Mangde Chu basin where an area increase is observed.

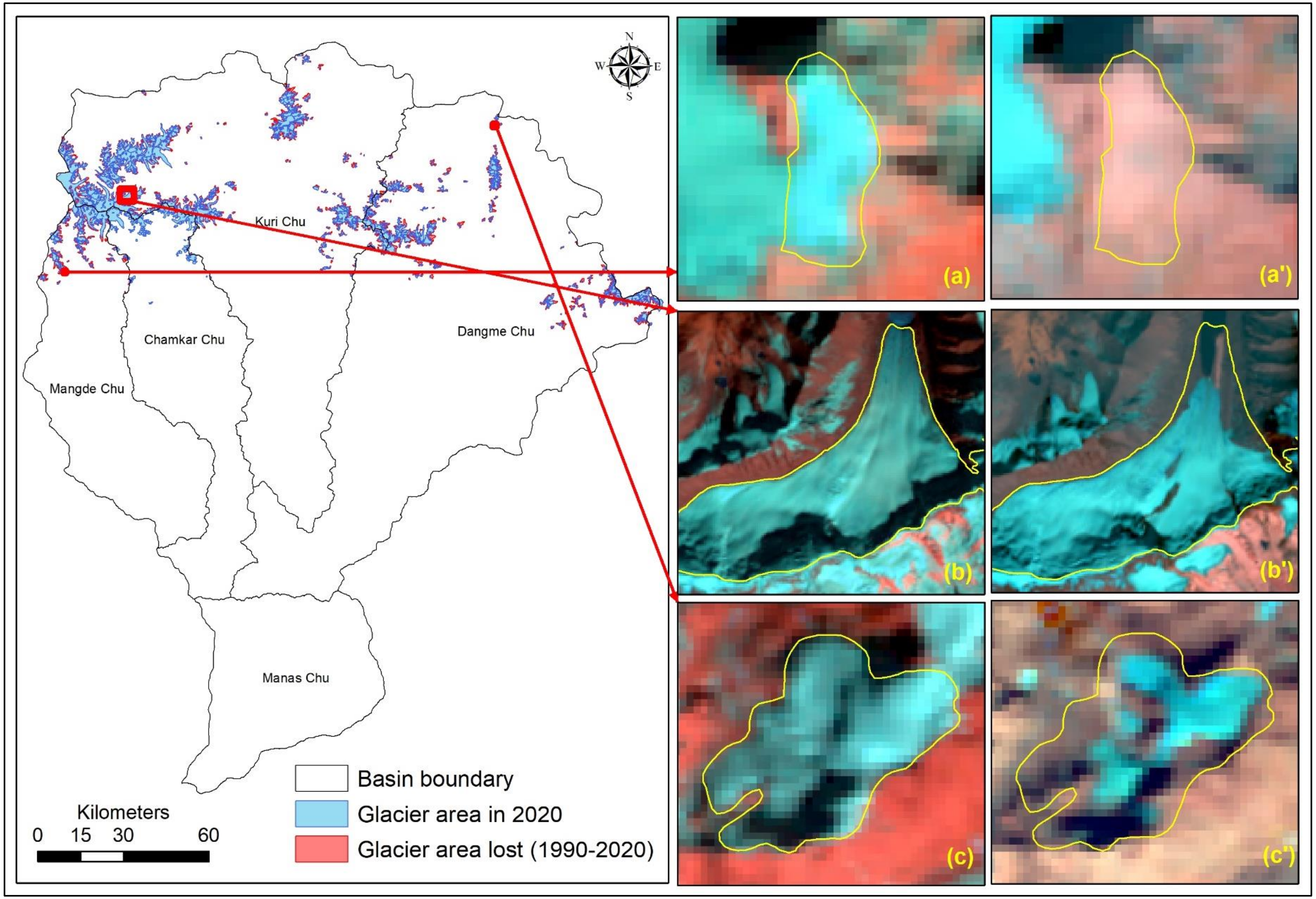


Figure 4.6 Glaciers identified in Manas-Beki basin in 1990 and 2020 with type of changes; glacier in 1990 (a) disappeared in 2020 (a′), glacier in 1990 (b) decreased in 2020 (b′), glacier in 1990 (c) fragmented in 2020 (c′)

Table 4.2 Types of changes in glaciers of Manas-Beki river basin and the affected areas during 1990–2020

Sub-basin	Disappeared		Decreased		Fragmented	
	No. of glaciers affected	Area affected (km^2)	No. of glaciers affected	Area affected (km^2)	No. of glaciers affected	Area affected* (km^2)
Mangde Chu	5	2.33	99	27.15	23	48.70
Chamkar Chu	10	2.23	81	23.52	13	26.23
Kuri Chu	7	1.58	484	157.08	11	141.11
Dangme Chu	20	5.10	329	130.64	61	91.46
Total	**42**	**11.25**	**993**	**338.39**	**108**	**307.51**

**Total area of the original glaciers in 1990*

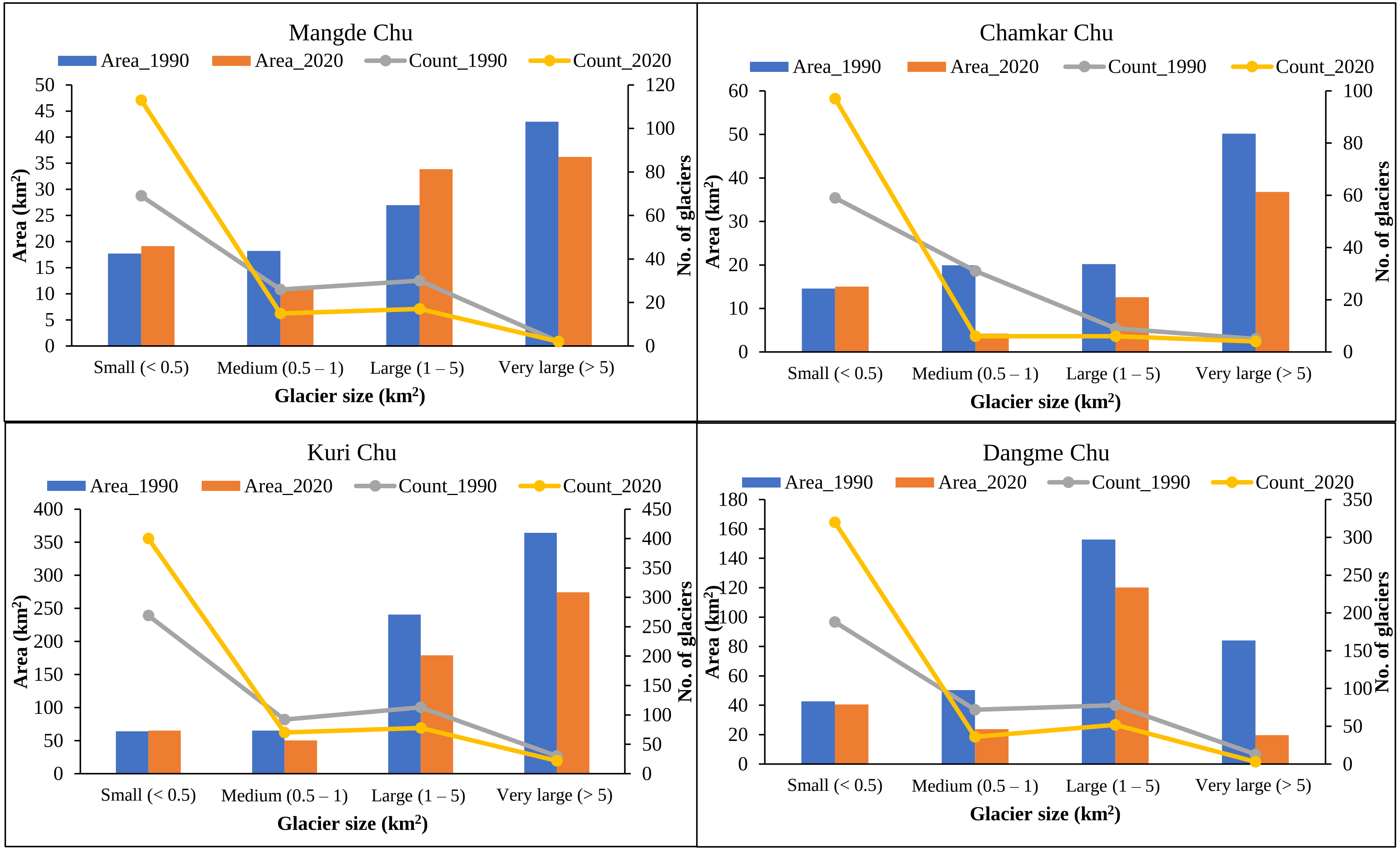


Figure 4.7 Area covered by glaciers (primary axis, bars) and number of glaciers (secondary axis, lines) under different size categories in sub-basins of Manas-Beki river basin in 1990 and 2020

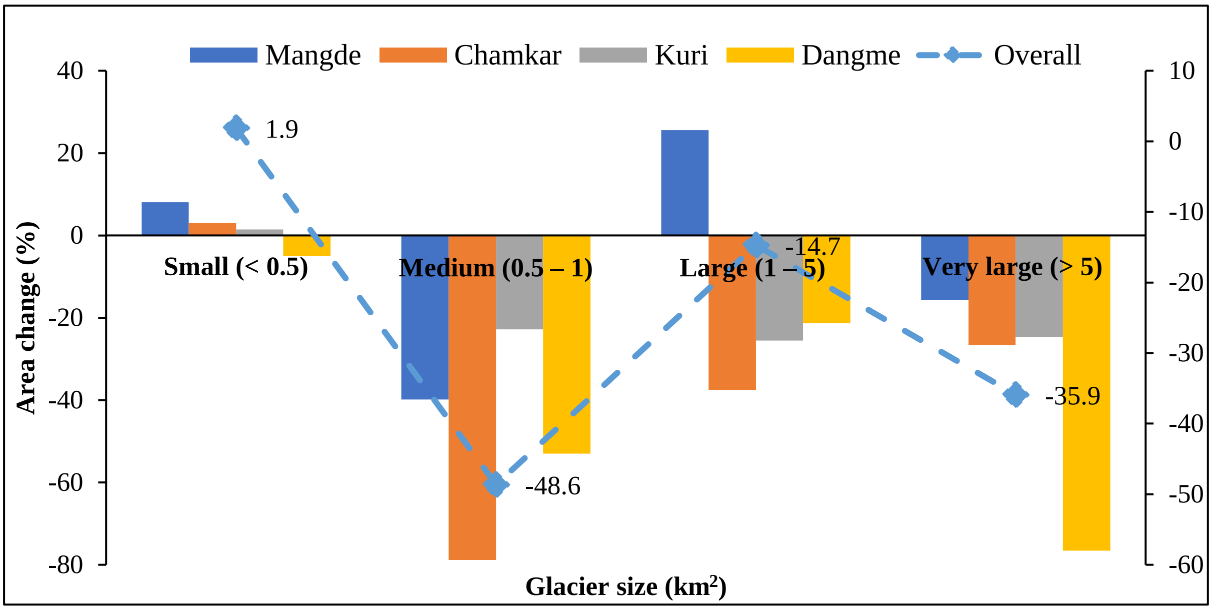
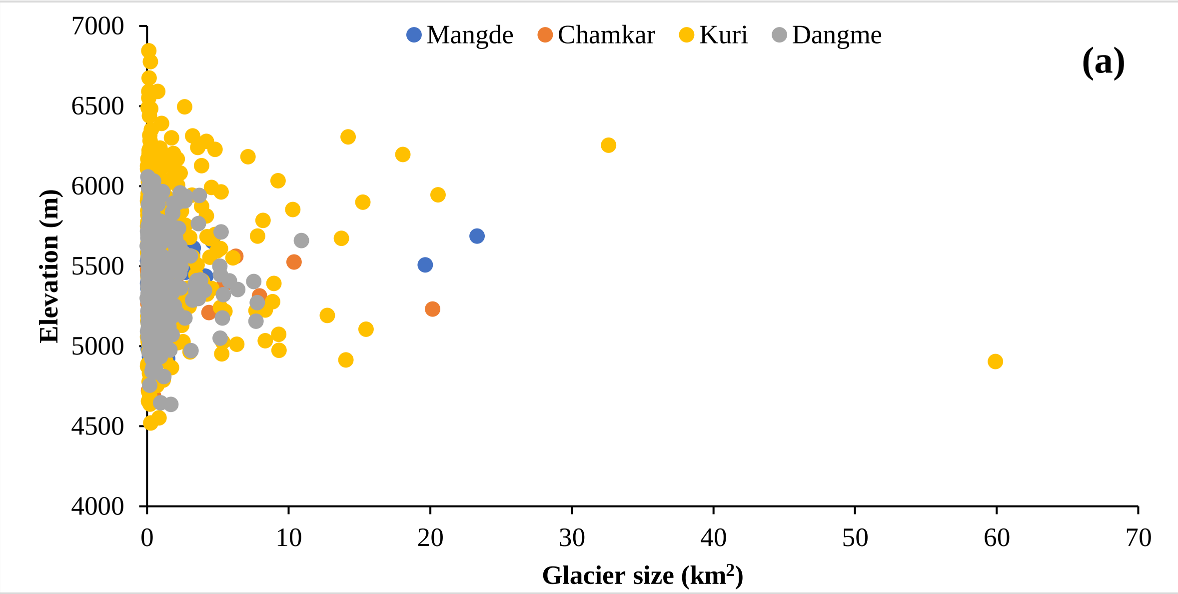


Figure 4.8 Percentage change in glacier coverage area based on different glacier sizes in Manas-Beki basin (1990-2020)

Altitudinal distribution of glaciers

The glaciers in the Manas-Beki basin lie within average altitudes of 4551 m to 6862 m (a.m.s.l.) in 2020. It is observed that in 1990, the lowest average glacier altitude and maximum average glacier altitude were lower at 4521 m and 6845 m (a.m.s.l) respectively. The distribution of glaciers based on size and elevation is given in Figure 4.9. For ease of understanding, elevation ranges of 100 m are clubbed together to calculate glacier coverage areas in each elevation range. The highest numbers of glaciers are in the range of 5200–6000 m elevations and the number decrease towards lower and higher altitudes.

The hypsometry graph of the glaciers shows that the altitudinal range of the glaciers in the study area lies between 4500 m and 7000 m (a.m.s.l.) (Figure 4.10). Glacier coverage shows a declining trend at almost all elevation ranges in the four sub-basins of the study area. The maximum glacier area of the Mangde Chu basin is in the elevation range of 5300–5600 m but the maximum loss in glacier area has occurred in the range of 5300–5400 m (~7.7 km^2) and 5100-5200 m (~7.2 km^2) altitude though decrease in area is observed at all elevation ranges. In the Chamkar Chu basin, the maximum glacier area is in the elevation range of 5300–5400 m and the maximum loss in glacier area has occurred in the range of 5200–5300 m (~9.3 km^2). For the Kuri Chu basin, it is observed that the highest glacier coverage is between a large range of 5000–6400 m altitude and the maximum loss in glacier area has occurred in the altitude range of 5200–5300 m (~15.4 km^2) though high decrease in area is observed between elevation ranges 5000 – 5700 m with an approximate loss of more than 10 km^2 glacier area in each range. The maximum glacier area of the Dangme Chu basin is in the elevation range of 5000–5800 m but the maximum loss in glacier area has occurred in the range of 5100–5200 m (~16.2 km^2) closely followed by 5200-5300 m (~16.1 km^2) altitude though a decrease in area is observed at all elevation ranges. The Dangme Chu sub-basin has recorded the highest loss in glacier coverage area at specific elevation ranges.



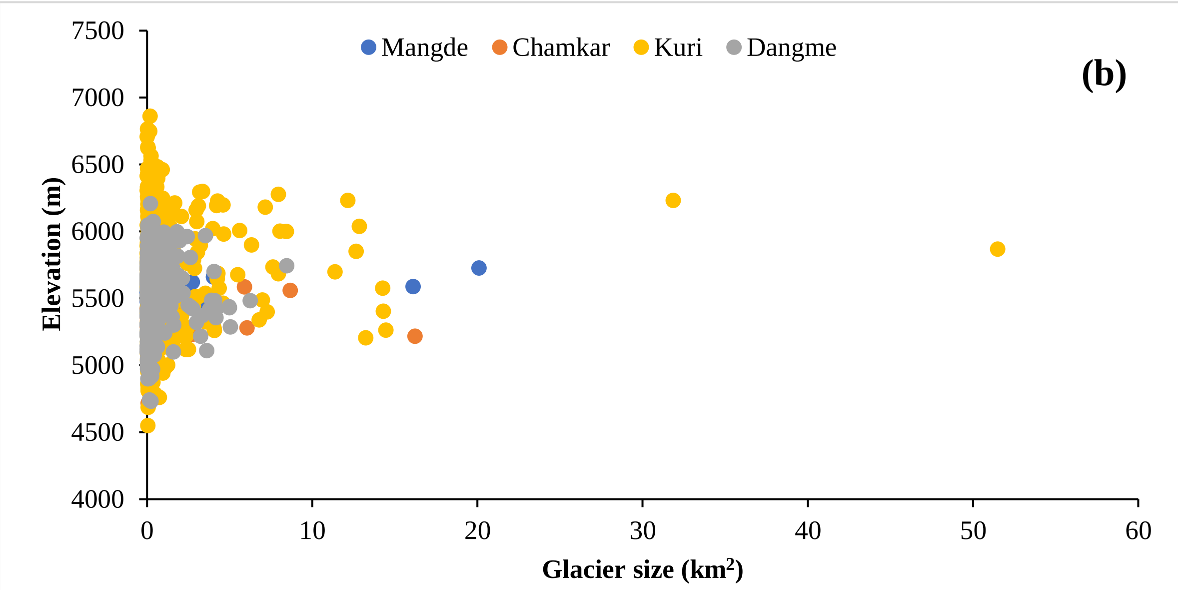


Figure 4.9 Glacier sizes under different elevation zones of Manas-Beki basin in (a) 1990 and (b) 2020

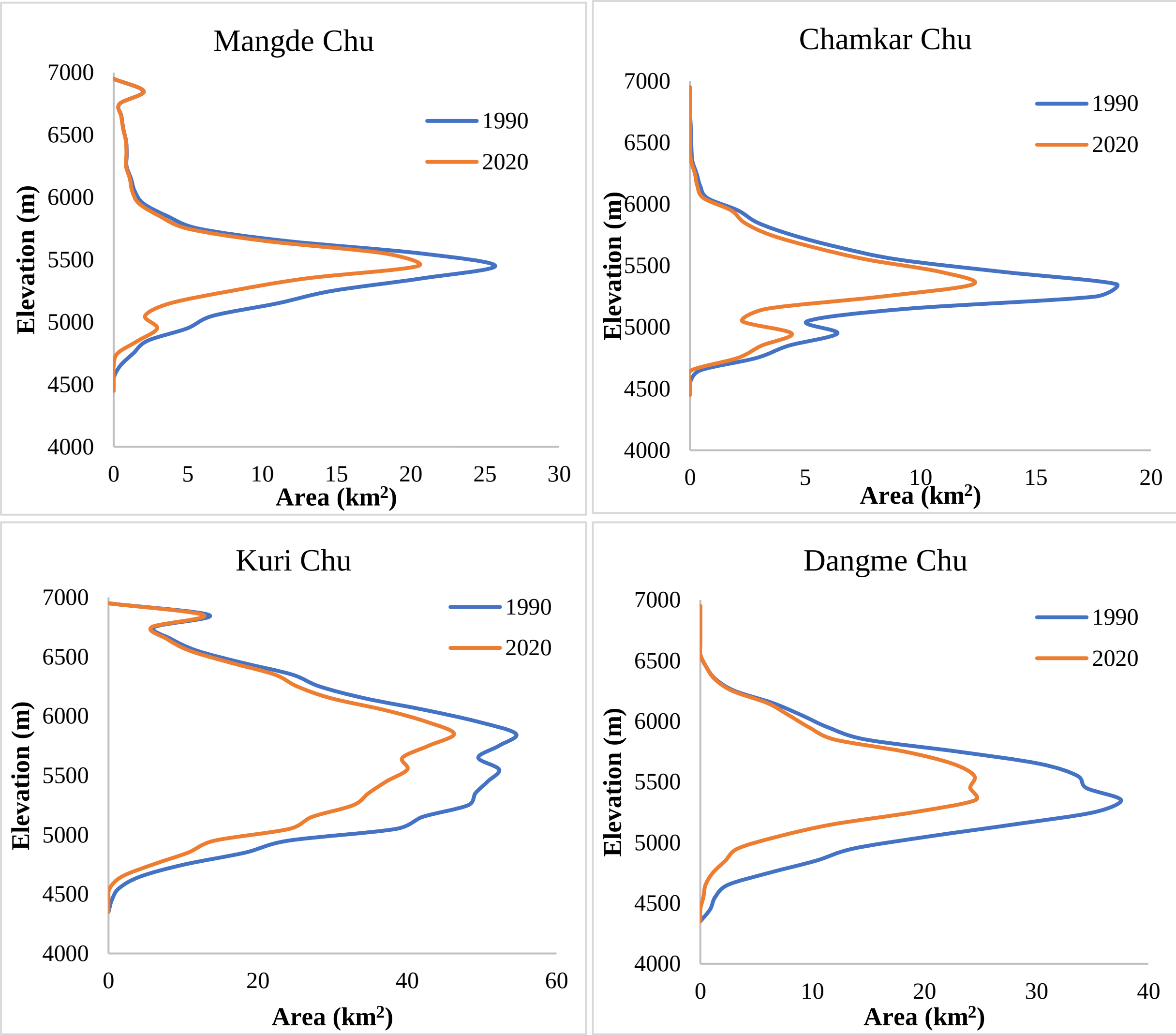


Figure 4.10 Altitudinal distribution of glacier area in the sub-basins of Manas-Beki river basin in 1990 and 2020

Aspect and slope of glaciers

The distribution of glaciers in the study area with respect to aspect was also analyzed (Fig. 4.11). The glaciers were oriented in different directions in the different sub-basins owing to the primary orientation of the basin. Between 1990 and 2020, the maximum change in the number of glaciers and glacier area was observed in the south and southeast directions for the Mangde Chu basin with only minimal decrease towards the other aspects. It is observed that though there are quite a number of glaciers oriented towards the north and northeast direction, the decrease in area in these aspects is much lesser than in the southern aspects. For the Chamkar Chu basin, it is observed that though most of the glaciers were oriented towards the northwest direction, the maximum area change between 1990 and 2020 is observed in the southeast and southwest directions. The glaciers in the Kuri Chu basin were primarily oriented towards the northern direction, with 55% of glaciers in the sub-basin with a north, northeast, and northwest orientation. The maximum change in glacier area (~52 km^2) is in the northeast direction, followed by north, east, and southeast. Similarly, in the Dangme Chu basin, more than 50% of the total glaciers in 1990 were oriented primarily towards the north, northeast, and northwest aspects but the major change in glacier area is observed in the east direction with a loss of ~27 km^2 area followed by northeast, north and west directions. The maximum and minimum percentage change in glacier cover area in the Manas-Beki river basin is observed in the Mangde Chu basin towards the southeast aspect and the west aspect respectively.

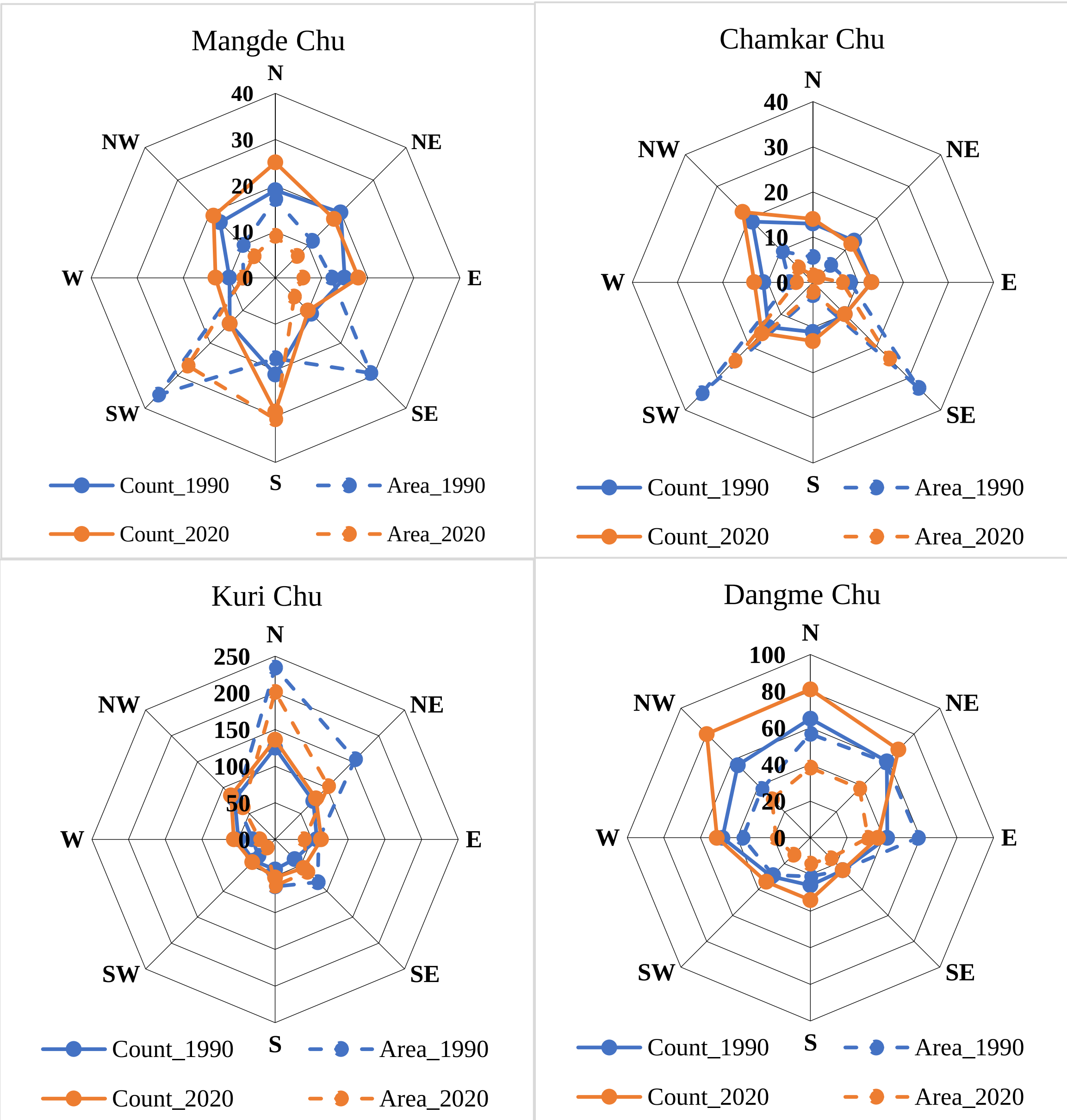


Figure 4.11 Distribution of glaciers in different aspects for the sub-basins of Manas-Beki river basin (1990 – 2020)

The average slope of maximum glaciers in the study area ranged between 10° to 50° but the maximum number of glaciers had an average slope of less than 10° followed by 15°–20°. The distribution of glaciers in the study area with respect to slope was also analyzed and Figure 4.12 shows the distribution in 1990 and 2020 for each glaciated sub-basin. In all the sub-basins except Dangme Chu, the maximum decrease in glacier area during the study period is observed in slopes less than 10° followed by 15° to 20°. In Dangme Chu, the maximum decrease in glacier area was observed in the range between 15° to 20°.

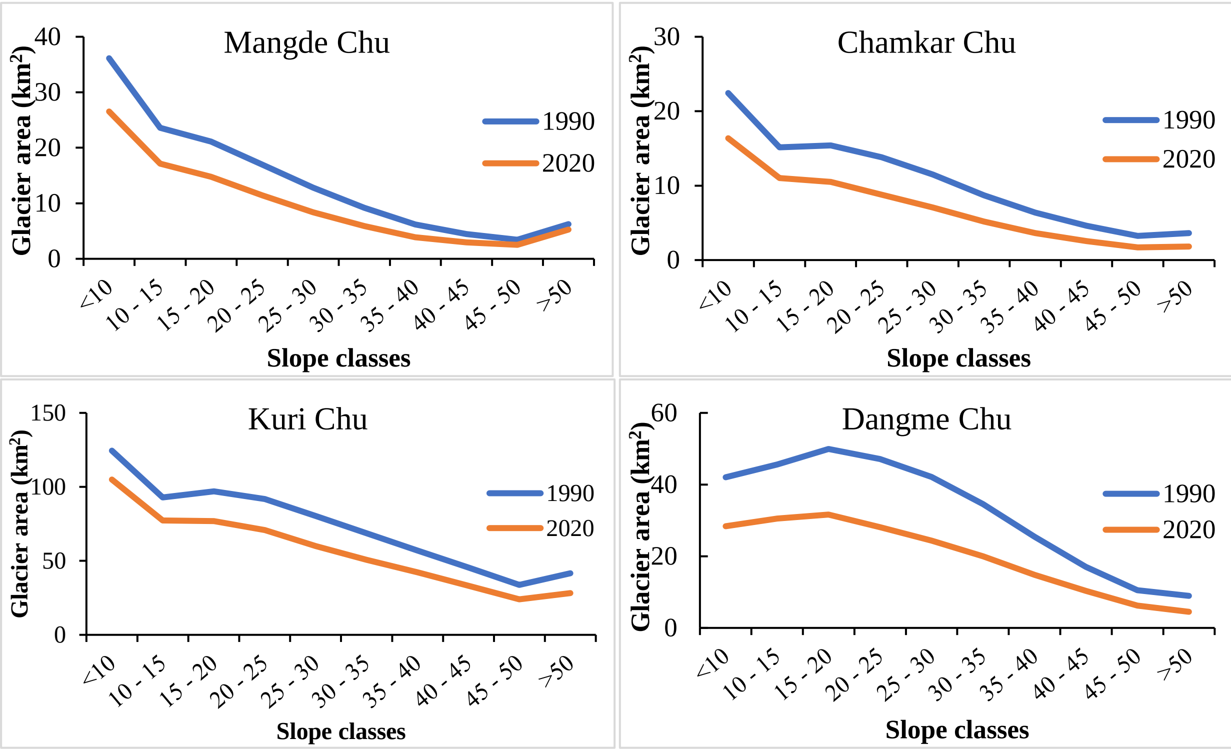


Figure 4.12 Distribution of glaciers in different slopes for the sub-basins of Manas-Beki river basin (1990 – 2020)

4.3.2 High-altitude lakes and changes

Extents of high-altitude lakes were extracted for 2020 for all the four glaciated sub-basins of the Manas-Beki upper catchment and changes were analyzed by comparison with lake extents extracted for 1990 to observe the changes in lakes in the river basin in the span of 30 years. Figure 4.13 shows the distribution of lakes identified in the year 2020. Lakes in the Manas-Beki river basin are classified into four different types on the basis of their relation to the location with respect to glaciers: moraine-dammed lakes are classified as 'pro-glacial lakes', lakes on the surface of the glacier at ablation zones are known as 'supra-glacial lakes', lakes that are away from glaciers, but glacier-fed are named 'unconnected glacial lakes' and those that are not fed by glaciers are known as 'non-glacial lakes' (Figure 4.14).

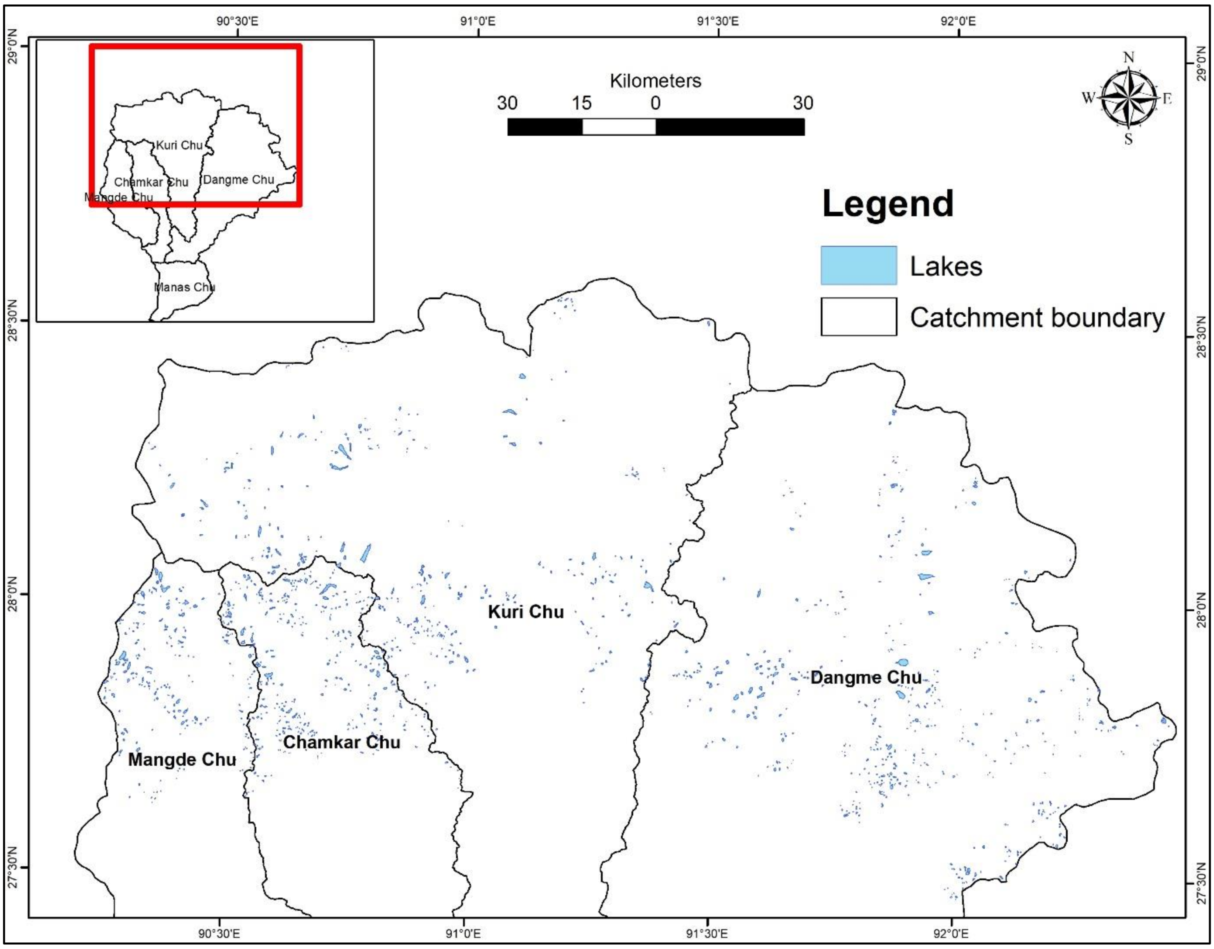


Figure 4.13 Distribution of high-altitude lakes in upper catchment of Manas-Beki river basin based on satellite data of 2020

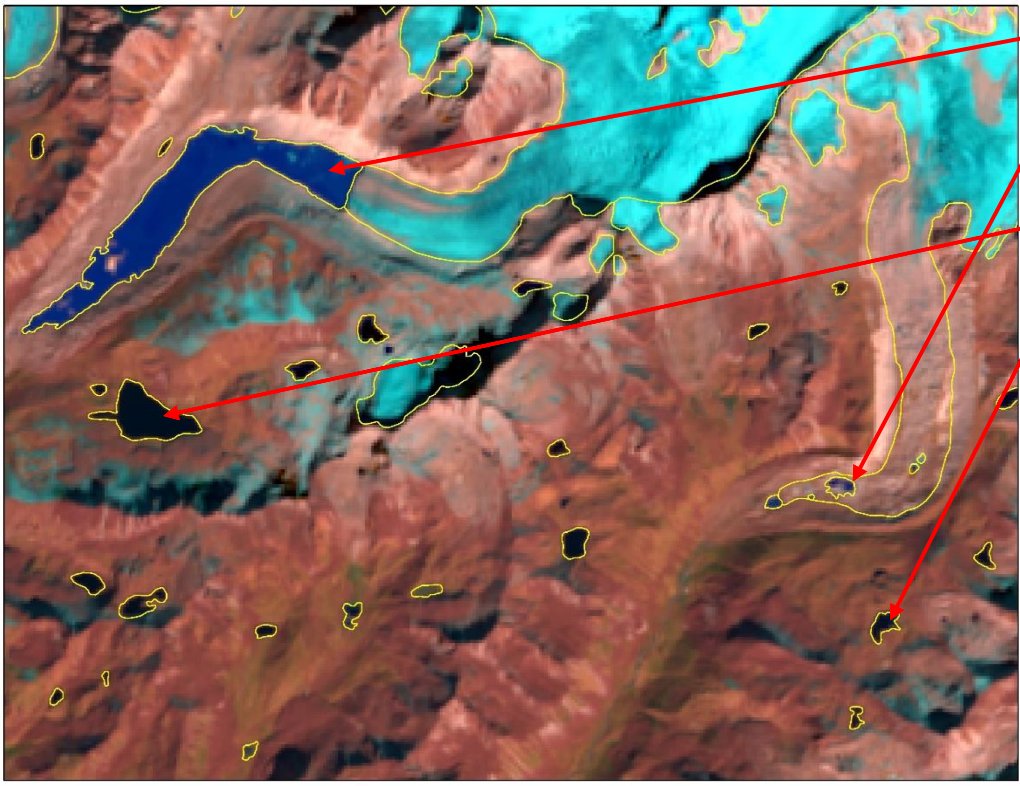


Figure 4.14 Types of high-altitude lakes in the Manas-Beki basin

Table 4.3 Types of changes in high-altitude lakes of Manas-Beki river basin and the affected areas during 1990–2020

Sub-basin	Year	Pro-glacial		Supra-glacial		Unconnected glacial		Non-glacial	
		No. of lakes	Area (km^2)	No. of lakes	Area (km^2)	No. of lakes	Area (km^2)	No. of lakes	Area (km^2)
Mangde Chu	1990	68	7.10	1	0.01	28	0.99	73	3.47
	2020	129	11.53	1	0.03	35	1.35	78	4.58
	Change	61	4.43	0	0.02	7	0.36	5	1.10
Chamkar Chu	1990	86	5.04	0	0.00	93	5.21	126	5.12
	2020	140	8.67	9	0.11	100	6.95	133	6.39
	Change	54	3.62	9	0.11	7	1.73	7	1.28
Kuri Chu	1990	109	11.01	0	0.00	213	11.36	10	0.48
	2020	182	19.58	10	0.13	231	13.38	10	0.60
	Change	73	8.57	10	0.13	18	2.02	0	0.12
Dangme Chu	1990	53	2.28	0	0.00	150	34.93	440	19.92
	2020	114	5.53	0	0.00	189	35.25	479	23.72
	Change	61	3.25	0	0.00	39	0.32	39	3.80

Analysis of high-altitude lakes reveals that lakes have increased in number as well as size in the study area during the last 30 years. A total of 1840 lakes were identified from satellite data analysis for 2020 and 1450 lakes were identified for 1990 with an estimated formation of 390 new lakes in the study area. Table 4.3 shows the quantitative changes in lakes and the distribution of different types of lakes in the study area. In 1990, an area of approximately 106.9 km^2 in the Manas-Beki basin was occupied by high-altitude lakes but in 2020, the area increased to ~137.8 km^2 with an area increase of ~30.9 km^2.

The major changes that have been noticed are an increase in lake sizes and the appearance of new lakes. It is observed that the highest number of lakes that have formed newly are mostly pro-glacial followed by unconnected glacial lakes, supra-glacial and non-glacial lakes except in the Dangme Chu sub-basin where the increase in new lakes is mostly in the non-glacial category. Both the non-glacial and unconnected glacial lakes showed an increase in the areal extent and numbers. There was only one supra-glacial lake identified in 1990 but in 2020, 19 new supra-glacial lakes are formed. Figure 4.15 shows the number and area of high-altitude lakes in the four glaciated sub-basins of the Manas-Beki river basin and the change is depicted in Figure 4.16. The bars indicate the number of new lakes formed under different types of glaciers in each sub-basin whereas the dotted lines indicate the increase in sub-basin-wise total area for each lake type.

Altitudinal distribution of glacial lakes

The altitudinal distribution of high-altitude lakes shows that they extend from 3800 m to 5800 m (a.m.s.l.) in the study area. Figure 4.17 shows the distribution of high-altitude lakes between 1990 and 2020 in each of the four glaciated sub-basins of the Manas-Beki river basin. In Mangde Chu, the maximum area of lakes was in the elevation ranges of 5200–5300 m and 5000–5100 m and the maximum increase in lake extent is in the higher elevation range of higher than 5200 m. It is observed that in 1990, there were no lakes above 5500 m (a.m.s.l) but in 2020, 13 new lakes have formed in these elevation zones. A similar trend is observed in Chamkar Chu basin where the maximum lake area was observed between 4700-5100 m. In 2020, 7 new lakes have developed above 5800 m where no lakes were observed in 1990. In Kuri Chu, the lake area is spread in different elevation zones with the maximum between 4600-4700 m followed by 5100-5200 m and 4200-4300 m. Maximum area increase is in the elevation range of 5200-5300 m and 39 new lakes have formed above 6200 m in 2020, where no lakes were present in 1990. For Dangme Chu, the maximum lake area is observed between 4800-

4900 m, but the increase is high in higher altitudes above 6000 m with the formation of 30 new lakes.

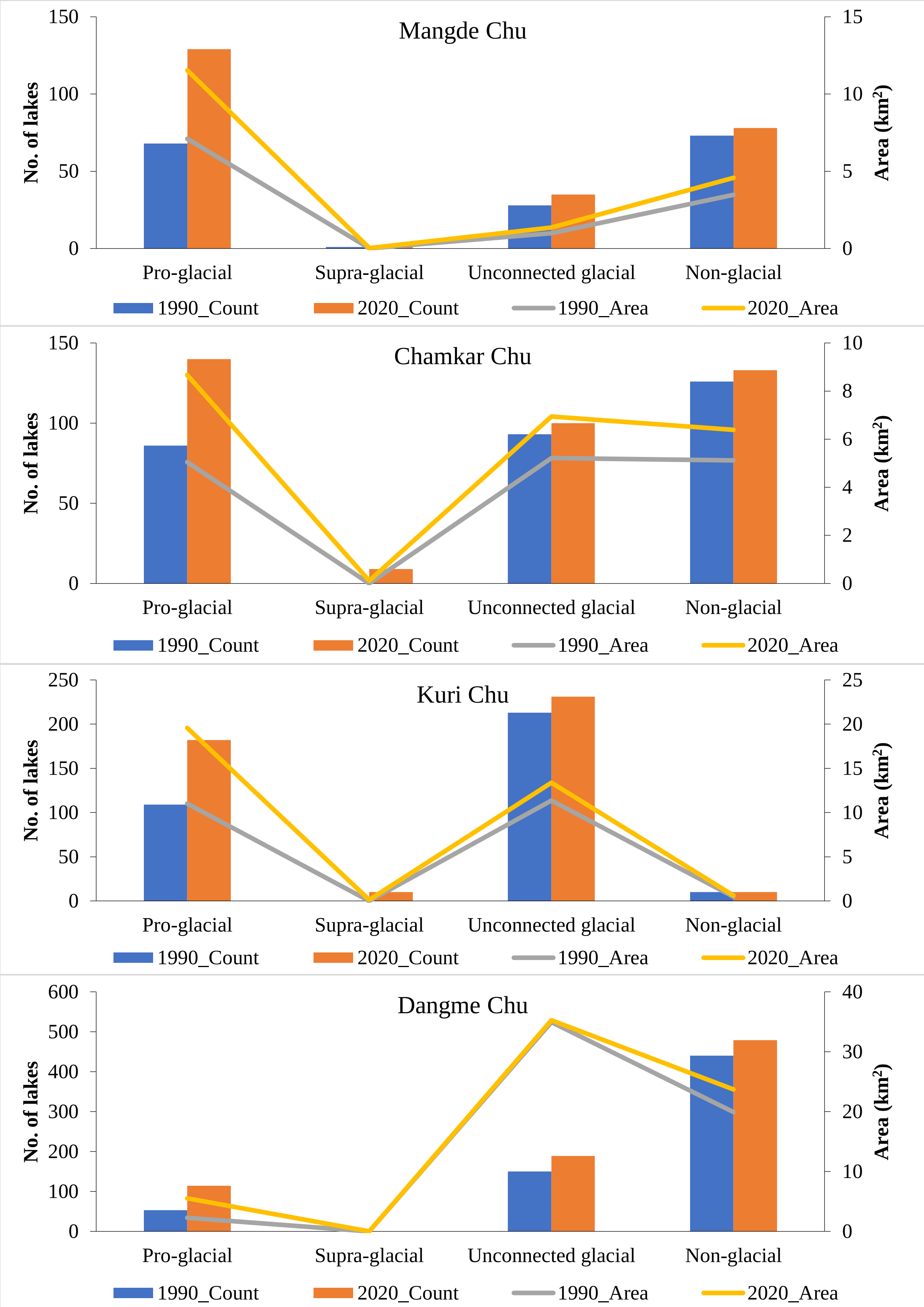


Figure 4.15 Distribution of lake types in 1990 and 2020 in sub-basins of Manas-Beki basin

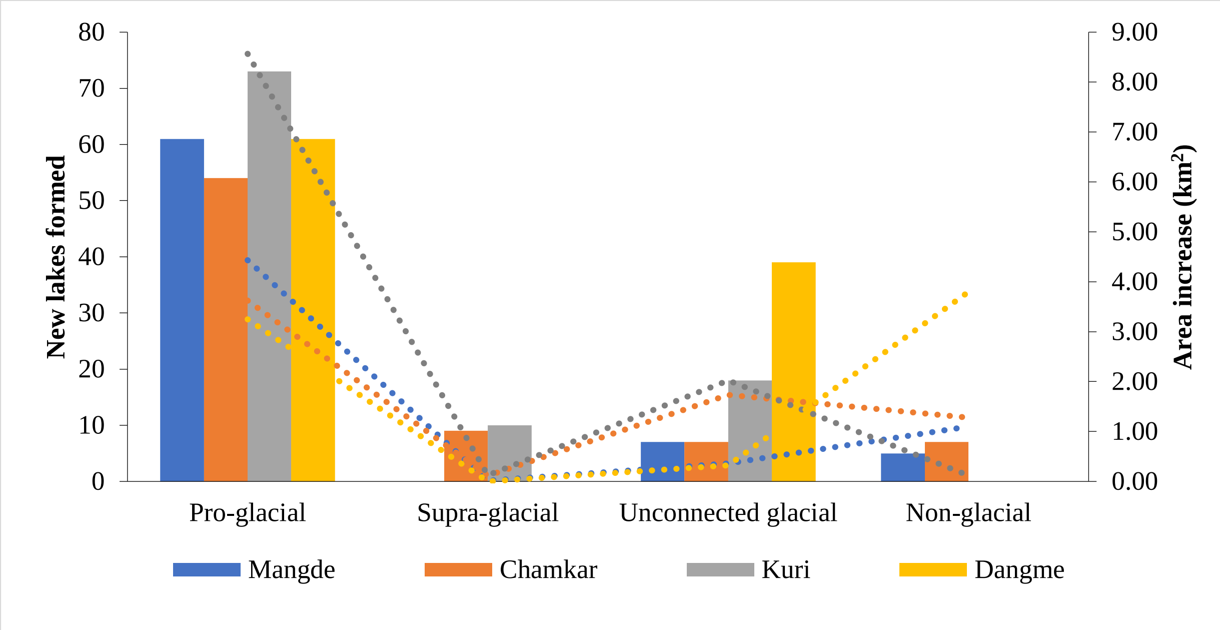


Figure 4.16 Changes in high-altitude lakes for sub-basins of Manas-Beki basin (1990-2020)

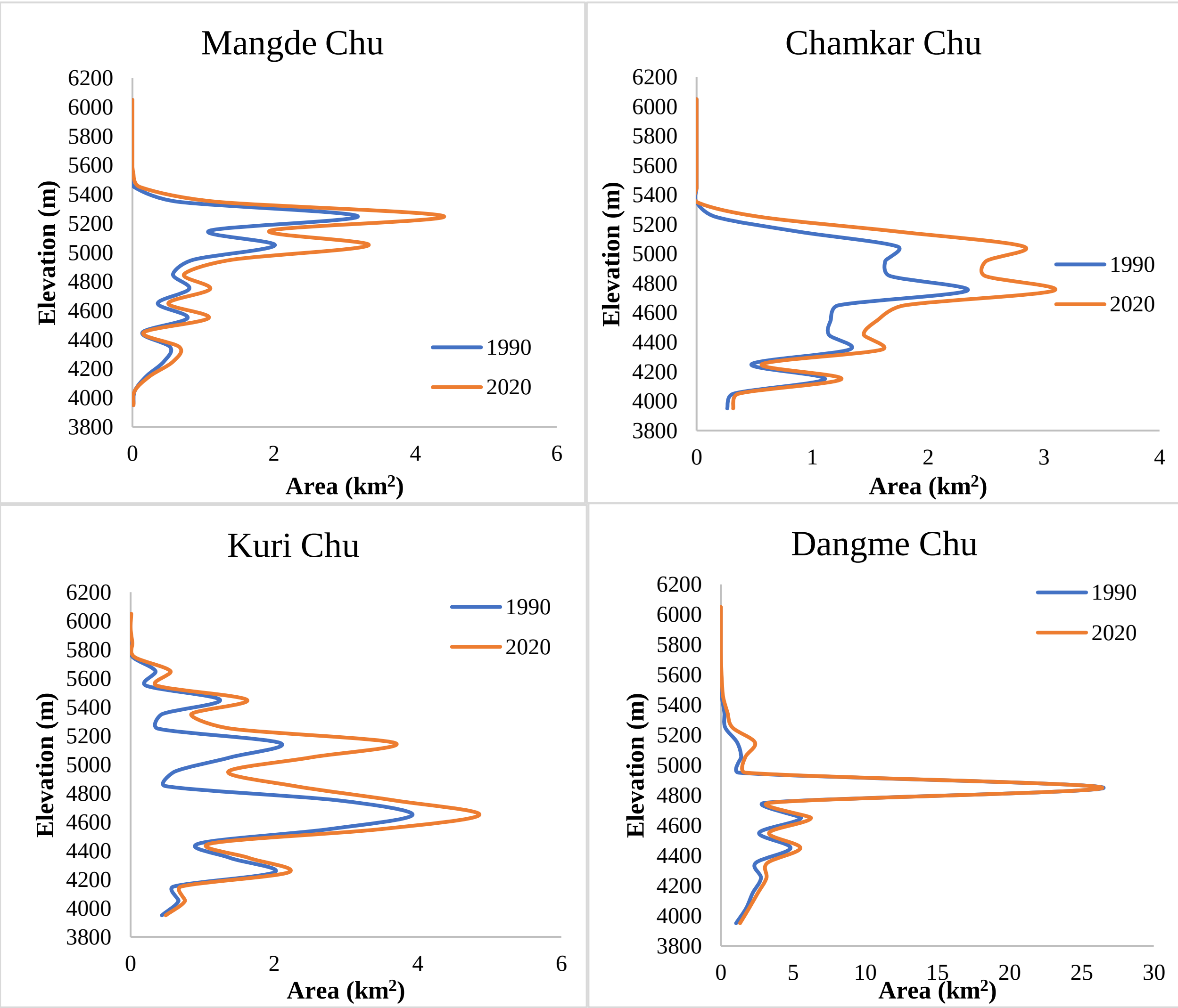


Figure 4.17 Altitudinal distribution of high-altitude lakes in sub-basins of Manas-Beki basin (1990-2020)

4.3.3 Analysis of gridded climate data

Mean monthly temperatures show a slight upward trend from 1990 to 2020 and analysis of winter and monsoon trends in temperature shows that temperatures have increased considerably in the monsoon months (June-September) compared to the winter months (November-January). The highest increase in mean temperatures is observed in the Manas sub-basin though all the sub-basins show a significant upward trend in mean temperatures during this season (Figure 4.18). Mean monthly temperature shows an upward trend during the winter months in all the sub-basins as shown in Figure 4.19. It is observed that the increase in temperature during the monsoon between 1990 and 2020 is higher in the lower elevation region of the Manas sub-basin while it is lower in the upper catchments. This trend is reversed during the winter season when the rate of mean temperature increase is lower in the Manas sub-basin compared to the upper catchments.

Total precipitation including rainfall and snowfall was also analyzed from ERA5 data for all the sub-basins to understand trends and seasonal variations. Though the mean monthly precipitation does not show any significant trend, but on analyzing the seasonal variations, a significant trend is observed during monsoon and winter months. Figure 4.20 shows the total precipitation in the monsoon season from 1990 to 2020 for each of the sub-basins in the Manas-Beki river basin and Figure 4.21 shows the total precipitation in the winter season. It is observed that during monsoon season, there is a slight increase in the precipitation over all the sub-basins except the Manas sub-basin where total precipitation comprising primarily of rainfall shows a declining trend over the years. During the winter season, the trend is declining in all the sub-basins comprising mostly of snowfall in the upper glaciated sub-basins.

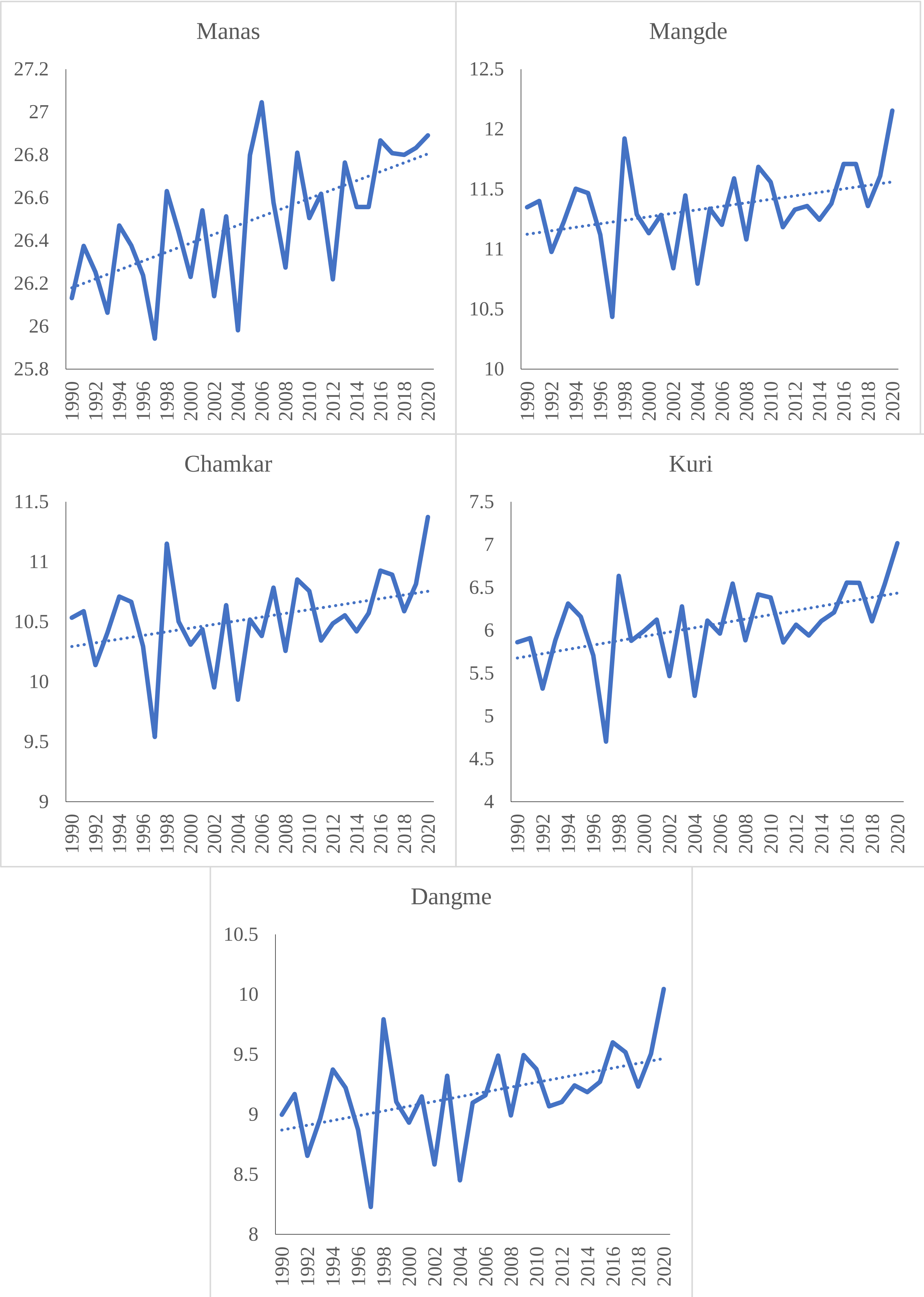


Figure 4.18 Monthly mean temperature (^{0}C) during monsoon season from 1990 to 2020 in sub-basins of Manas-Beki river basin

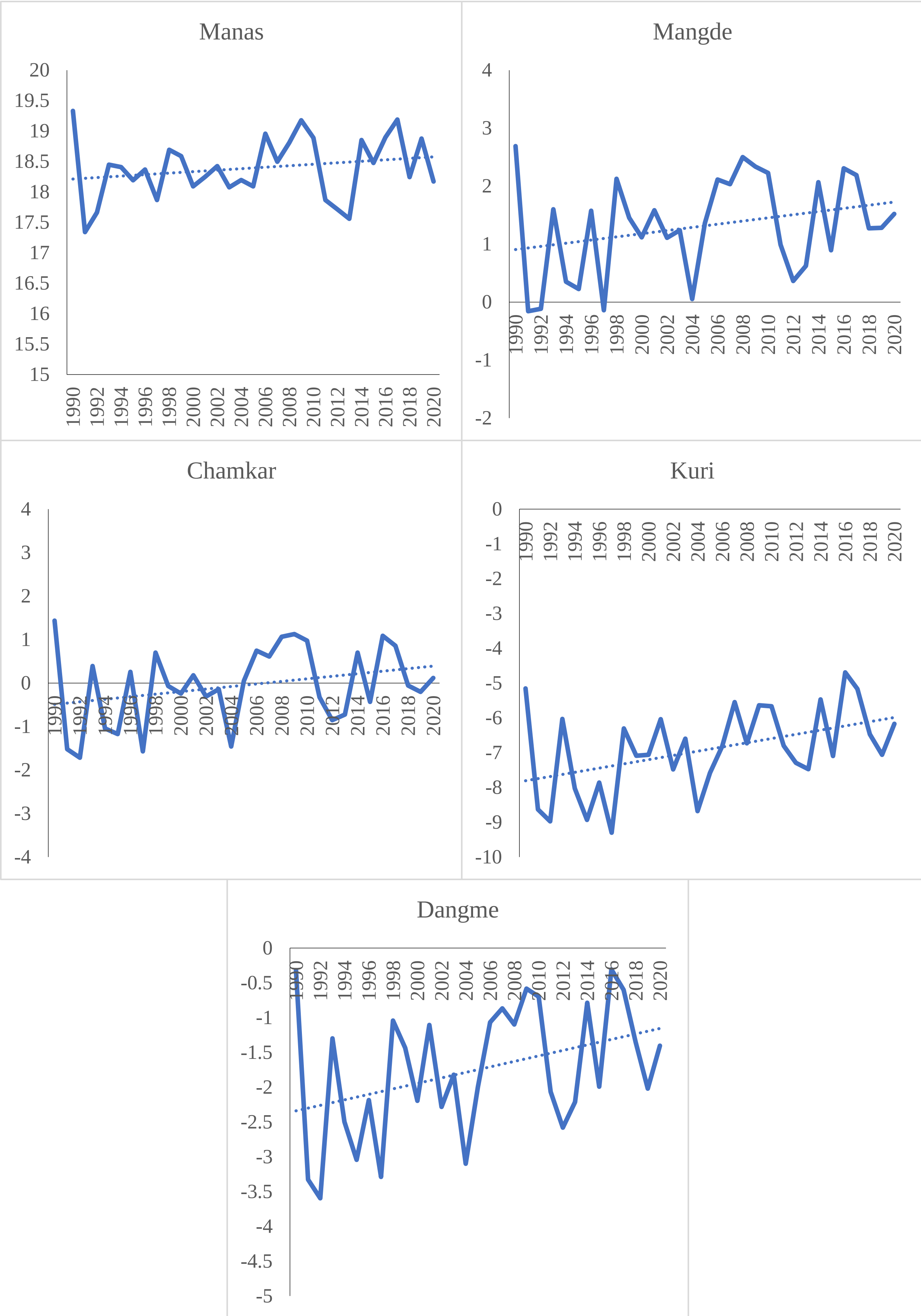


Figure 4.19 Monthly mean temperature (^{0}C) during winter season from 1990 to 2020 in sub-basins of Manas-Beki river basin

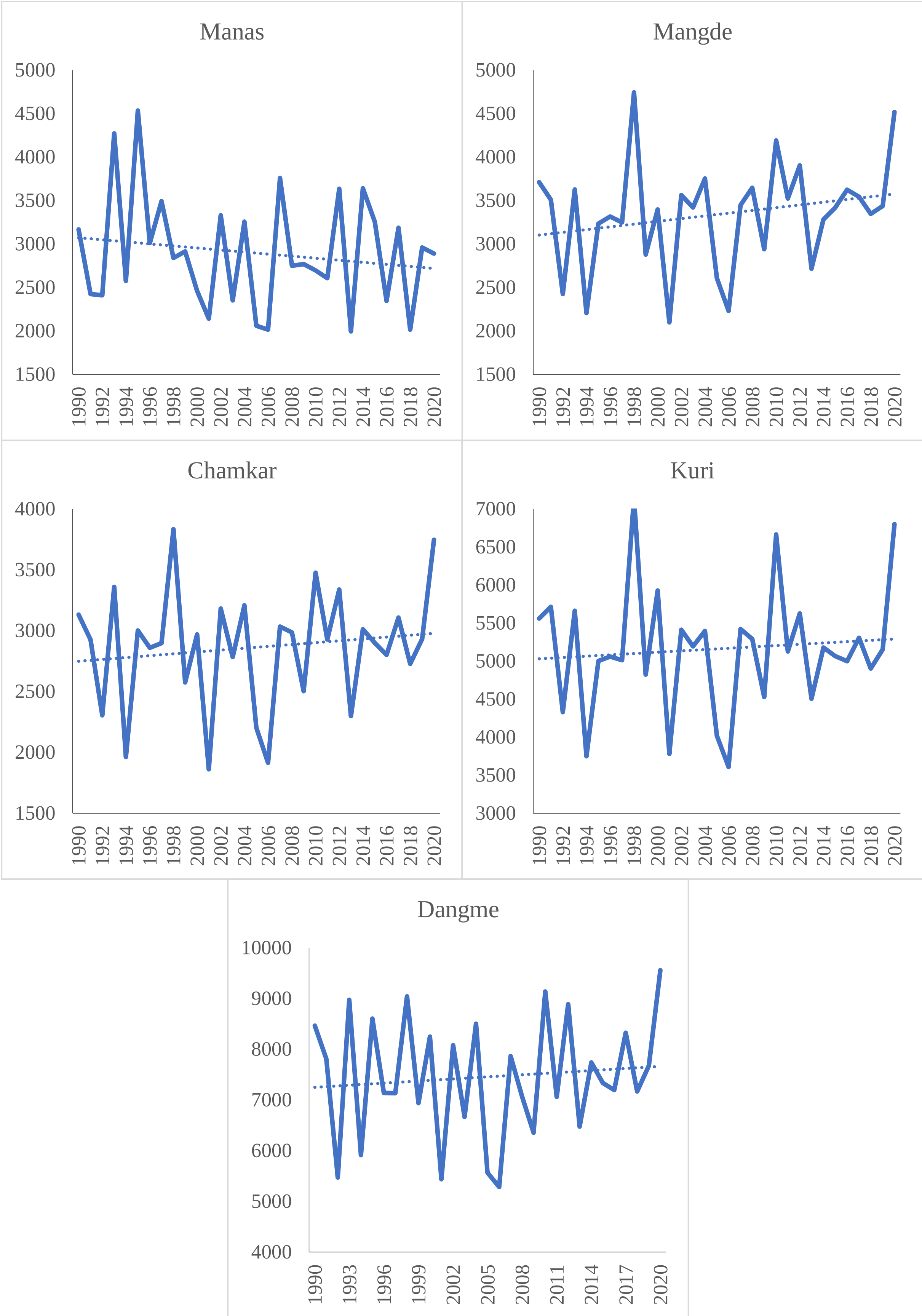


Figure 4.20 Monthly total precipitation (mm) during monsoon season from 1990 to 2020 in sub-basins of Manas-Beki river basin

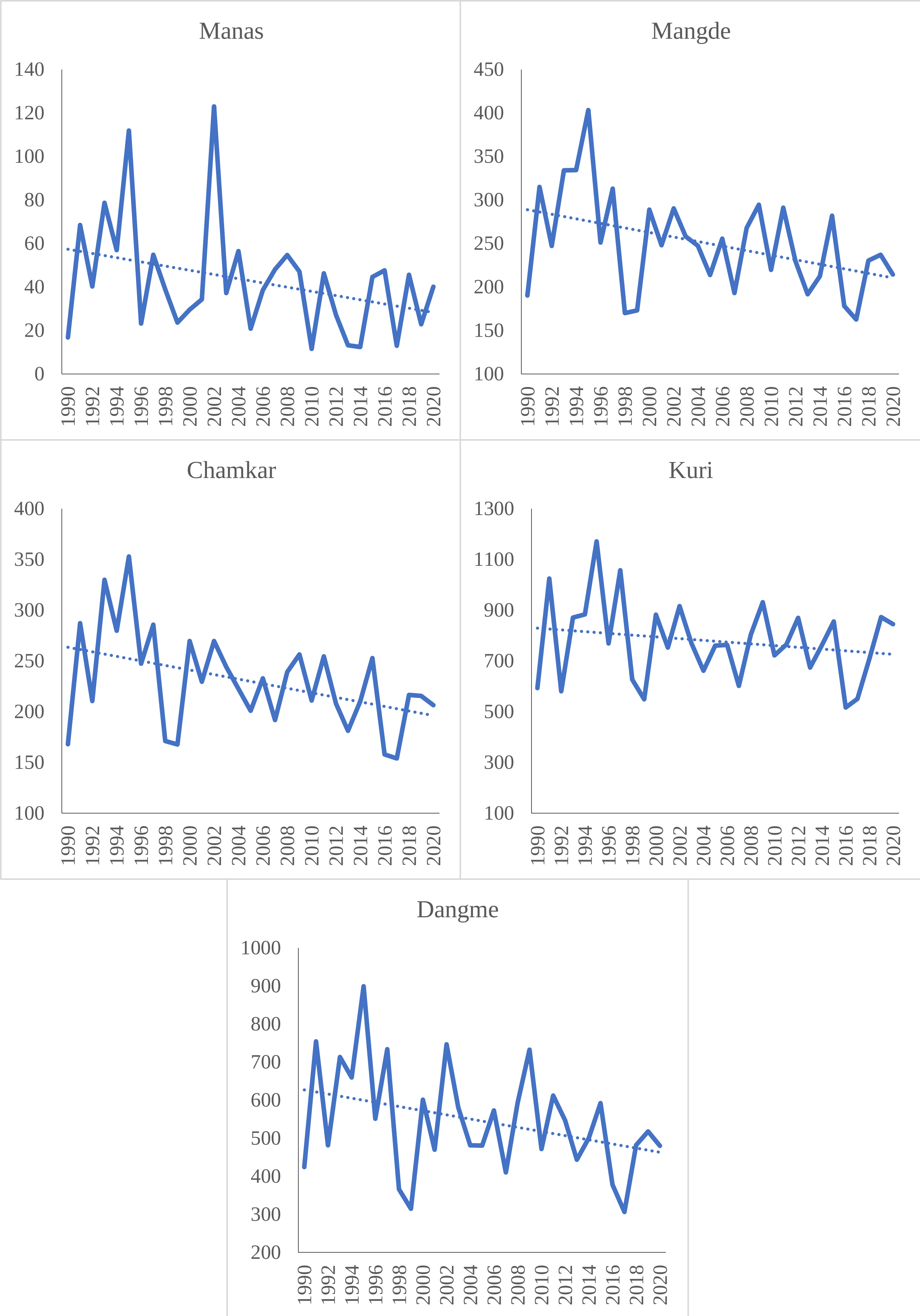


Figure 4.21 Monthly total precipitation (mm) during winter season from 1990 to 2020 in sub-basins of Manas-Beki river basin

4.4 Discussion and summary

The Himalayan region remains one of the most intriguing zones for glacial regime due to its vast expanse of glacier coverage, freshwater resource, and associated high-altitudinal glacial lakes [64, 92-95]. The analysis in the current study revealed a remarkable decline in both the number and area of the glaciers during the three decades in the Manas-Beki river basin which was also observed in a study carried out for the Dangme Chu (Bhutan Himalaya) basin [69]. A similar trend has also been reported by various researchers for the Eastern Himalayas, especially in the Kanchenjunga region, Sikkim, and parts of Bhutan [56, 57, 96]. The smaller glaciers were more susceptible to area changes and disappearance in comparison to larger ones, as the response of the larger glaciers to environmental changes is lower resulting in more stability [57, 96]. Ageta et al. reported that the altitudes of the glaciers in Bhutan Himalaya are situated above 4000 m (a.m.s.l.) [97]. The hypsometry graph showed that the area decrease in glaciers was more prominent at the middle elevations (5300–5500 m). Researchers also reported that the rate of area loss in the Sikkim glaciers was slower at higher altitudes (above 5750 m in Kanchenjunga), which is due to a lower ablation process [69, 96, 98]. The results indicate higher melting of glaciers in the southern aspects (south, southeast, and southwest) which may be due to the fact that the south-facing slopes receive higher solar insolation in the northern hemisphere. Racoviteanu et al. also reported greater glacier area loss towards south-facing slopes in Nepal, Sikkim, and Bhutan Himalayas [57]. Considering the glacier changes with respect to aspect and slopes, there is a possibility of GLOFs occurrence at the slope range of 20° to 25° and towards the south-western aspect of the study area.

In contrast to glaciers, the high-altitude lakes showed an increase in both size and number in the Manas-Beki river basin during the study period. These findings are in consistence with the results of Veettil et al. who observed that the frequency and area of the glacial lakes increased between 1990 and 2010 in the Dangme Chu basin, which is a part of the study area [69]. Similar phenomena have also been reported from other parts of the eastern Himalayan region such as Bhutan, Nepal, and Sikkim [56, 57, 61, 79, 99]. The expansion or formation of new lakes is mainly due to the glacier retreat leading to moraine-dammed lakes (pro-glacial lakes), a phenomenon commonly observed in the Himalayas [69]. The expansion of lakes in the Tibetan plateau has been linked to the increased runoff from snow and glacier melt due to increasing temperatures and precipitation in the region [100]. However, as compared to non-glacial lakes, a greater increment was observed in the unconnected glacial lakes. This may be due to the increase in water volume fed by glacier melting and the formation of lakes due to the glacial retreat of nearby glaciers resulting in new unconnected glacial lakes. On the other hand, the increase in non-glacial lakes can be attributed to the glacier melt in the entire hydrological basin [37]. The results indicate that new lake formation and increase in lake extent are greater in higher altitudes. This may be due to the fact that lakes at higher altitudes are directly linked to glaciers (pro-glacial lakes) and glacial melt/retreat is the major reason for the increase in area and formation of new lakes [69]. As observed in the results section, the maximum area loss in glaciers is in the elevation range of 5300–5400 m also indicating that glacial melt has contributed from these elevations to the lakes downslope.

Climate variability in the study area is indicated by an increase in mean monthly temperature and a predominant decrease in precipitation with some exceptions observed from the reanalysis dataset. Similar trends were observed by Shrestha and Devkota in the Eastern Himalayas though the variability in precipitation was negligible [55]. The sequence of retreat of glaciers, formation of pro-glacial lakes, and subsequent occurrence of GLOF events triggered by rock falls, avalanches, earthquakes, and calving of ice cliffs are one of the chief concerns in the region [69, 95, 101].

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