Spatiotemporal quantification of key environmental changes in Stok and Kang Yatze regions of Ladakh Himalaya, India

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Abstract:

Tourism fuelled economic transformation of Ladakh region is bringing a change in demography and livelihood preferences leading to increased exploitation of scarce natural resources. In addition to the nerve centre of tourism-related activities (Leh city), rural hinterlands of Ladakh are also witnessing a stark transformation in land and resource use patterns. In this study we quantified and assessed the changes in key environmental parameters of rural Ladakh between 1969 and 2020. We observed a decrease in glacier area, glacier volume and vegetation cover by ~19%, 13% and 14%, whereas built-up and lake area increased by ~238% and 122%, respectively. Simultaneously, local population of the region doubled while tourism footprint increased by ~620 folds. The study highlights the environmental changes happening at a higher rate in rural regions around Leh city. Therefore, need of the hour is to recognise the disruptive changes being brought in the traditional way of life and to devise strategies to reorient the development paradigm towards sustainable resource use and management.

Keywords: Ladakh, tourism, environment, climate change, glacier, Himalaya.

1. Introduction

Mountainous regions in Himalaya face various sustainability challenges due to climate, geopolitical, economic, and societal transformations, which affect environment, water resources and demography of the land (Bhardwaj et al. 2019). Some of the major factors for such transformations are the climate change (Sam et al. 2019), booming tourism industry, international conflicts, rapid urbanisation and migration. These factors will have both positive and negative impact on the environment and society. Positive impacts comprise of warmer climate more conducive to habitation, improvement in living standards and economy, agricultural growth, and improved connectivity, among others. However, the negative impacts are often long-lasting, irreversible, and more damaging, and consist of excessive stress on the environment, unplanned development, exploitation of natural resources, and pollution, among others. Policy design and implementation is challenging in mountains, because usually these regions have been of marginal concern due to lesser population, and therefore often ignored in development priorities (Messerli and Ives 1997; Geneletti and Dawa 2009). Environmental fragility and tourism seasonality of mountain regions further add to the issues hindering systematic and integrated developments (Buckley et al. 1999; Arrowsmith and Inbakaran 2002; Geneletti and Dawa 2009). Moreover, mountain areas often mark international borders for many countries and thus, hold political sensitivity in terms of major policy changes (Nepal and Chipeniuk 2005). With increasing globalisation and political stability in majority of the world, mountain tourism has developed with an accelerated pace in the past several decades (Price 1992; Moss and Godde 1999). However, such tourism has led to unprecedented growing environmental concerns in developed (Draper, 2000) and developing countries alike (Stevens, 2003, Buntaine et al., 2006).

One of such mountainous regions is Ladakh which used to be a restricted land for the outside world due to its geo-strategic sensitivity (Bray, 1991; Warikoo et al., 2020) and tribal population (Smith, 2012). However, the government of India opened the region for tourism in 1974 (Bray, 1991), which marked the beginning of a new era for Ladakh. As per the data available from the Leh tourist office, 8,608 Indian and 16,256 foreign tourists visited Ladakh in 1988 (Bray, 1991). Thus, tourism emerged as the prime revenue generator for the region and opened new income sources for guesthouses and hotels, local shops, and guided tours and travels (Bray, 1991; Nüsser, et al., 2019a,b; Müller et al., 2020). However, the initial economic benefits of tourism had been concentrated in the Indus valley, disproportionately benefitting mainly non-Ladakhis (Michaud 1991). With improvements in connectivity and communication, this scenario has evolved in the past two decades as the number of visitors increased many folds over last few decades from a few hundred in 1974 to more than 300,000 visitors in 2019 from every corner of the world (Muller et al., 2020). Agriculture used to be the primary sector for the local economy but today it is replaced by tertiary sector (especially tourism) (Dame et al., 2019; Muller et al., 2020). Leh, which is the capital city of Ladakh, has now become one of the most visited cities in high-Himalayan Mountains. The recent decision to develop Ladakh as a Union Territory of India has cleared the path for more rapid urbanisation and development of the region in coming years.

While rapid urbanisation of Leh city has recently been investigated from a remote sensing perspective (Dame et al., 2019, Müller et al., 2020), the effects are still unknown for the rural areas around Stok and Kang Yatze range. As mentioned above, such regions along the Indus valley have been the target of this tourism-led changes in Ladakh (Michaud 1991; Nüsser et al., 2012). Thus, for these regions, it is particularly important to quantify the changes in several of the key environmental parameters such as glaciers, vegetation, water, and built-up, between 1969 and 2020, to understand the long-term impacts of tourism and demographic changes on high-mountain catchments. In this study we are trying to understand and document the major land cover changes happened in the parts of rural Ladakh for the past 50 years (1969-2020).

The main objectives of this research are: (1) to perform temporal mapping of glaciers, vegetation, water, and build-up in Stok and Kang Yatze regions of Ladakh Himalaya; (2) to quantify spatiotemporal changes in the mapped parameters; and (3) to use climate, demography, and other ancillary datasets for further assessing the quantified changes.

2. Study area

In this study, two different adjacent regions (Stok and Kang Yatze region) with various glaciers, build-up, vegetation, and population settings were selected from Ladakh, India (Figure 1) to understand the changes occurred due to climate change, tourism, and urbanisation during past five decades. The geographic extent of the study area lies within latitude and longitude of 33.3º to 34.3º N and 77.1º to 78.1º E, respectively. It covers a vast area around Stok and Kang Yatze regions extending from 3000 to 6400m a.s.l in the northern Zanskar range, Ladakh, India. The region of interest consists of 15 villages of various sizes with population ranging from 128 - 5,565 individuals (Census 2011). Most of these villages are entirely dependent on the glacier and snow meltwater for irrigation and domestic use. Stok and Kang Yatze regions house 30 and 106 glaciers of various sizes ranging from 0.01 to 5 km^2, with larger glaciers (>3 km^2) entirely concentrated in Kang Yatze region. In 2019 the total glacierised area was around 89 km^2, equivalent to 3.2% of the study area.

Ladakh, the newly formed Union Territory of India, has a unique climate with extremely arid and cold environment. As per the longest in-situ data available from the region headquarter Leh (3500m a.s.l), the long-term yearly mean precipitation sum is <100 mm whereas the mean annual temperature is ~5.6 ºC (Nüsser et al., 2012; Soheb et al., 2020). The region is also a hub for wildlife and climbing enthusiasts for its diverse flora fauna and the two famous peaks of Stok (6140m a.s.l.) and Kang Yatze (6400m a.s.l.) summit. Apart from agriculture and service sector, tourism has developed as a major driver of the local economy of the region in the current times (Dame et al., 2019; Müller et al., 2020). Figure 1 presents the study area and the key environmental parameters within the region.

3. Data and methods

In this study, we used freely available multiple datasets from various sources to understand the transformations in key environmental parameters such as vegetation, build-up, glacierised areas, water bodies, and demography (Table 1). The information on multisource datasets used within this study are provided in Table 1. Below we provide descriptions of used datasets and methods for each of the objectives.

3.1.Glacier mapping

For glacier mapping, Orthorectified level-1T Landsat-Thematic Mapper (TM) and Operational Land Imager (OLI) images (www.earthexplorer.usgs.gov) with minimum (<30%) cloud cover from ablation period (August-September) were used to map the glacierised region of different time periods (1991, 1998, 2010 and 2019). Several robust and established methods to map glaciers are available in literatures e.g. Band ratio approach (Paul et al., 2002, 2015; Racoviteanu et al., 2009; Bhardwaj et al., 2014; Bhardwaj et al., 2015; Schmidt & Nüsser, 2017; Smith et al., 2015; Winsvold et al., 2014, 2016), supervised classification methods (Muhammad et al., 2013; Khan et al., 2015; Nagai et al., 2016; Tian et al., 2017; Muhammad 2019), and manual delineation method among others.

In this study, glacier mapping was carried out by closely following the Global Land Ice Measurements from Space guidelines (Raup et al., 2010). We used the ratio approach between Near Infrared and Shortwave Infrared bands with a threshold of 2.0 (NIR/SWIR > 2 = ice/snow). A median filter of kernel size 3 x 3 was applied to remove the isolated and small pixels outside the glacier area. The NIR and SWIR band ratio approach is good at distinguishing glacier pixels from water features with similar spectral reflectance values

(Racoviteanu et al. 2009; Zhang et al. 2019). Band ratio technique doesn't perform well in shadowed regions therefore additional manual corrections was required (Muhammad and Tian 2016). This method is robust and time-efficient for mapping clean glacier (Paul and Kaab, 2005; Andreassen et al., 2008) and fortunately the study area only consists of clean glaciers.

Multiple high resolution PlanetScope images (www.planet.com) of 29 August 2018 and Google Earth were also used to improve the mapping for the current extent of glaciers. The extent of glaciers in the accumulation zone were kept unchanged throughout the mapping periods because no significant changes is expected in these regions, and also this approach helps in minimising the error in mapping a glacier (Bolch et al., 2010; Bhambri et al., 2013; Garg et al., 2019).

Six Corona KH-4A images (www.earthexplorer.usgs.gov) from 30 July 1969, with minimum snow cover, were used to extract the historical extent of glaciers of the study area. Owing to the complex geometry of corona imagery, 12 subsets were made for the study area. All the subsets were separately co-registered following the steps performed by (Bhambri et al., 2011). A projective transformation using ground control points (GCPs) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model (ASTER DEM) was performed followed by a spline adjustment in ArcGIS 10.5. Stable boulders, stupas, historical sites, Monasteries, road junctions and bridges among others were used to collect GCPs. The primary focus of the Corona image rectification was to georectify the glacierised and build-up areas. Digitization of 1969 glacier outlines were manually carried out on the corrected Corona image subsets.

3.2.Glacier thickness and volume estimation

ASTER DEM from two periods at a temporal gap of atleast 10 years, with no cloud cover over glaciers of the study area, from the ablation time was required to estimate the volume of these ice masses of the study area and see the changes over time. DEM from 2004 and 2020 satisfied the conditions and were chosen for further analysis. The ASTER DEM products (AST14DMO) are created using only orbital ancillary data and without GCPs, therefore small outliers (peaks and sinks) are likely to be present in DEMs. These outliers were removed using the method followed by Shukla and Garg, 2019. Relative horizontal and vertical biases are often present in DEMs derived from different sensors (Nuth and Kaab, 2011). In the present study, we observed a slight shift in the DEMs from the same sensor for the two periods (2004 and 2020). Therefore, the three-dimensional coregistration of the DEMs was required to be performed on stable areas (least error prone regions, e.g., flat valleys, grass lands and farms among others). We followed the coregistration method developed by (Nuth and Kaab, 2011) to minimise the horizontal and vertical biases. The glacierised areas were first removed from the DEMs followed by the areas with a slope between 4-45 degrees, cloud cover, large outliers (elevation difference >±100m) and pixel elevation below 4000m a.s.l. (as no glacier is present in this region below this elevation). The horizontal shift between the reference and slave DEM was corrected significantly. The X and Y shift was reduced from 26.5 and 23.81 m to 4.13 and 3.45 m, respectively. However, the vertical biases available in the DEMs were corrected using all (> 20,000 pixels) the reliable elevations differences over the stable terrains (Nuth and Kaab, 2011). Furthermore, we have used these temporal bias-corrected DEMs as input in GlabTop and GlabTop2 models to estimate glacier volumes rather than change in surface volume (or DEM differencing). The models have their own uncertainties, as discussed in the later section, which are well-above any jitter-induced errors and did not make any notable difference in the GlabTop model results.

The bias corrected DEMs were further used to estimate the volume of glaciers of the study area. We estimated the volume using three different methods, i.e., Glacier Bed Topography model (GlabTop2), shear-stress/slope dependent (hereafter slope dependent method) and area-related methods. GlabTop2 model is the upgraded version of the previous GlabTop model developed by (Linsbauer et al., 2009) where the thickness is estimated at several points along the glacier branch lines further interpolating to the entire glacier (Linsbauer et al., 2009; Paul and Linsbauer et al., 2012; Frey et al., 2014). In the advanced GlabTop2 model, the thickness is calculated for randomly selected DEMs pixel within the glacier inner cells (or glacierised area). Thickness of all other glacier cells are estimated by interpolating the thickness at random cells and the ice thickness at the glacier marginal cells (or along glacier margins) where ice thickness is known to be zero (Frey et al., 2014; Ramsankaran et al., 2018). The calculation is distributive, requires only DEM and glacier outline as input and uses Equation 1 (Cuffey and Paterson, 2010; Haeberli and Hoelzle, 1995).

$$hf = \frac{\tau}{f\rho\, \mathrm{g} \sin(\alpha)} \qquad (1)$$

where

τ = average basal shear stress along the central flow line

f = shape factor (60-90; Cuffey and Paterson, 2010)

ρ = density of ice (900 kg m^{-3})

g = acceleration due to gravity (9.8 m s^{-2})

α = mean surface slope

The value of basal shear stress (in kPa) is estimated using an empirical relationship between basal shear stress and glacier elevation range (ΔH, in km) as per Equation 2 (Haeberli and Hoelzle, 1995)

$$\tau = \begin{pmatrix} 0.5+159.8\,\Delta H-43.5\,(\Delta H)^2 & \Delta H \leq 1.6\ km \\ 150 & \Delta H > 1.6\ km \end{pmatrix} \qquad (2)$$

Slope dependent method uses the same equation (1 and 2), as Glabtop and Glabtop2 model, to calculate the average thickness of a glacier. To account the semi-elliptical cross-sectional geometry of a glacier, a multiplication with 0.785 is added to equation 1. This method has been applied extensively by many (Hoelzle et al., 2007; Paul and Svoboda, 2009; Salzmann et al., 2013). However, area-related thickness estimation only uses surface area of the glacier and other scaling parameters. It is the most frequently used method because of its simple and fast implementation. Equation 3, given below, is used for area-related thickness estimation.

$$H = cA^{\gamma} \qquad (3)$$

Where

H = mean thickness of glacier

c and γ = scaling parameters given by Chen and Ohmura (1990) who used 63 glaciers and Bahr et al. (1997) who used theoretical analysis to determine these parameters.

The obtained thickness from slope-dependent and area-scaling method was then used to calculate the volume of glaciers with the help of glacierised areas of the respective years. The pixel-based thickness obtained from the GlabTop2 model was first applied to calculate the volume of each pixel and further summing up all the pixel to get the volume of individual glacier volume.

3.3. build-up, vegetation, and water body mapping

Both Corona and PlanetScope images were used to map the built-up, vegetation and water bodies of 1969 and 2018, respectively. Owing to lesser heterogeneity of the landscape, a supervised classification technique on 1969 and 2018 images was used to distinguish between vegetation and non-vegetation land in ArcGIS 10.4, with additional manual correction where needed. The classification process included 15 training samples containing >30,000 pixels combined to improve the classifier's overall performance. Built-up area of 2018 were manually digitised on screen using high resolution PlanetScope image. The 2018 results were overlaid on the 1969 corona image as a reference to digitise the built-up area of 1969. The built-up areas of 2018 which were not present or cannot be identified on 1969 images were removed from 1969 built-up areas. The built-up areas which no longer exist at present but were present in 1969 also mapped and added. Water-bodies were mapped manually on screen on both Corona and PlanetScope images.

3.4.Climate data analysis

In addition to the satellite imageries, long-term ERA5 monthly single level reanalysis climate data have also been used in the study to understand the climatic settings of the study area. ERA5 (downloaded from https://climate.copernicus.eu/) is a 5th generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis high resolution climate data at 0.25 degrees. The data carries a large set of variables from 1979 to present. In this study, monthly mean temperature and precipitation data was used. In-situ data from Leh, India (nearest in-situ data available) was used to bias correct the ERA5 temperature and precipitation. Kanda et al., 2020 evaluated the performance of seven grid-based datasets against the observed data from 19 in-situ stations across the region of Karakoram, Greater and Lower western Himalaya and found that ERA-Interim (precipitation), and CRU-TS and ERA-Interim (temperature) are the best performing datasets in all these regions with additional bias corrections. ERA5 is the improved version of ERA-Interim and can be used for further analysis (Figure 4).

Linear scaling bias correction (Ines and Hansen 2006; Teutschbein and Seibert 2012, Shrestha et al 2016) was adopted for ERA5 data correction with the help of Leh in-situ data. The bias corrected Leh data was statistically analysed to understand the magnitude and significance of trends using Mann-Kendall test and Sen's slope estimator (Sen, 1968), respectively. The change in temperature and precipitation (Table 2) was calculated using Equation 4 following Shukla et al 2020:

$$Change = (\beta \times L)/M \qquad \textbf{(4)}$$

Where β is Sen's slope estimator, L is the length of the period and M is the long-term mean.

3.5. Uncertainty assessment

Our study involves extraction of various key environmental parameters utilizing multiple satellite data and methods. Hence, there are different sources of uncertainties related to the approaches used in the present study. Therefore, in this section we present the methodologies that were used to estimate the uncertainties.

3.5.1. Uncertainties in glacierised area and volume:

Since there is no available in-situ reference data for large set of glaciers in this region. Therefore, we estimate the error term based on a buffer based assessment for each glacier following the methods of Bolch et al., 2010; Granshaw & G. Fountain, 2006; Mölg et al., 2018; Tielidze & Wheate, 2018. The buffer width was set to half-pixel as the glaciers of the study area are debris free. The half-pixel buffer was applied to the glacier polygons and area was recalculated. The overall uncertainty was ~ ±3.4% with individual uncertainties of ± 0.6, 3.9, 4.0, 4.1 and 4.2% for 1969, 1991, 1998, 2010 and 2019 images (Table 3).

For GlabTop2 and Slope dependent method the uncertainties were estimated based on error propagation method (Kumari et al., 2021; Ramsankaran et al 2018; Frey et al., 2014) by modifying the scaling parameters. Since the variation in these parameters are unknown for the study area, ±5% of uncertainty was considered for τ, f (Driedger and Kennard 1986; Haeberli and Hoelze, 1995; Kumari et al 2021; Ramsankaran et al 2018) and ±10% was considered for the density of ice (ρ) following Gantayat et al. (2014). The uncertainty in the term u (sin α)/sin α was assumed to be ±0.2 considering the potential uncertainty of ~20m in ASTER DEM in the Himalayan region (Bhambri et al., 2011; Toutin 2008). The uncertainty in the area-related volume estimation was determined by comparing the influence of the two applied scaling parameter sets on the results with additional modification of ±5% in individual glacier area (Frey et al., 2014). Table 4 present the associated uncertainties.

3.5.2. Uncertainties in other environmental parameters:

The uncertainty in the build-up and lake area was estimated based on a comparison between the independently generated outlines in two sample villages (Chuchot and Stok) and all the lakes by three different analyst on the same satellite images. For vegetation cover, a stratified random sampling design was used to determine the sample numbers and their position on the map. For the purpose we have selected ~500 points on both Corona and PlanetScope images. The accuracy assessment was done by determining the probability of a particular cell value being similar to the actual generated classified information (i.e. vegetation cover). Error matrix (also known as confusion matrix or covariance matrix) and kappa coefficient was calculated for both Corona and PlanetScope. Details of the uncertainties are presented in Table 5.

4. Results and discussion

4.1.Overall change in key environmental parameters between 1969 and 2021

We analysed several key environmental parameters in the study area, i.e., glacierised area and volume, built-up area, vegetation area, lake area, and demography between 1969 and 2021. Due to limitations in temporal datasets, the time periods for the analyses are different. The glacierised region was mapped for 1969, 1991, 1998, 2010 and 2019. Glacier volume was estimated for 2004 and 2020 due to non-availability of cloud-free DEMs before 2004. Built-up, vegetation and lake areas were analysed for two periods (1969 and 2018) because publicly no high-resolution images exists in between. The population data is also not available after census 2011, therefore population of 2021 was extrapolated through a regression developed using available datasets of from 1971, 1981, 2001 and 2011 census reports.

4.1.1. Overall change in glacierised area and volume

Stok and Kang Yatze watersheds consist of 30 and 106 glaciers, larger than 0.01 km^2, covering an area of 10.6 and 78.5 km^2, respectively. These glaciers retreated over time with varying retreat rates during different periods. Glaciers of Stok region retreated at a rate of 0.26, 0.35, 0.6, and 0.57% per year during the periods 1969-91, 1991-98, 1998-2010, and 2010-19, respectively. Total change observed over 50 years was 2.51 km^2, equivalent to 19% (0.38%/year) of the total glacierised area. Whereas, Kang Yatze region observed a slightly different rate of change during individual periods. However, total change (in %) in glacierised area over 50-year period was similar to Stok region, i.e., 18.7 km^2, equivalent to 19% (0.38%/year). The retreat rate in Kang Yatze was found to be 0.38, 0.28, 0.62, and 0.33% per year for 1961-91, 1991-98, 1998-2010, and 2010-19, respectively. Overall, glacierised area changed from 110.4 km^2 in 1969 to 89.21 km^2 in 2019 with a change of 21.2 km^2, equivalent to 19% (0.38%/year) of the glacierised area over 50-year period. These changes are however higher than the changes observed by Negi et al., 2021 and Shukla et al, 2020 in the adjacent region of Shayok (Karakoram region) and Suru (Kargil region) where the retreat was reported to be 7.8% (0.008%/year) and 6% (0.2%/year), respectively. Negi et al., 2021 studied 569 glaciers of size greater than 1 km^2 of Shayok region between 1991 and 1994. Whereas, Shukla et al., 2020 studied glaciers larger than 0.01 km^2 between 1971 and 2017. However, Schmidt and Nüsser, 2017 studied glaciers (> 0.03 km^2) of Stok, Kang Yatze and the region nearby between 1969-2016 and found results similar to the present study. These results are interesting considering that our study area is the most populous and tourism-prone within Ladakh region, and the significantly higher glacier retreats clearly point towards a plausible connection between glaciers and threatened microclimate. Figure 2, 3, 5 and 8 presents the area changes over 50-year period while Figure 4 provides the data on climate changes in this region.

Two (GlabTop2 model and area-scaling method) of the three methods used in this study to estimate the thickness of these ice masses gave similar results; however, the third method (slope-dependent method) gave comparatively lower thickness estimate. Volume of glaciers in Stok region using GlabTop2, area-scaling and slope-dependent method was found to be 0.29, 0.31 and 0.22 km^3, respectively, for the year 2004; and 0.23, 0.27 and 0.17 km^3 for the year 2020, respectively. Volume of glaciers in Kang Yatze region using GlabTop2, area-scaling and slope-dependent method was found to be 3.2, 3.1, and 2.1 km^3, respectively, for the year 2004 and 2.6, 2.8, and 1.7 km^3 for the year 2020, respectively. Figure 2, 3, 5 and 8 present the average values of these estimates over 16-year period. The average (of the three different estimates) change found over the 16-year period was 0.05 and 0.37 km^3, equivalent to 18% and 13% (1.1 and 0.8%/year) in the total ice reserve of Stok and Kang Yatze region, respectively. The study area currently holds ~2.5 Gigaton (Gt) of water with 0.21 and 2.5 Gt of water in the glaciers of Stok and Kang Yatze regions, respectively.

Changes in the glaciers of high-altitude Himalayan region are generally due to the rise in temperature, orientation, debris and black carbon among others. However, in the region around Leh, these changes are also associated with the lower winter precipitation (Soheb et al., 2020). Region around Leh (study area) generally receives comparatively less precipitation (Figure 4) (Soheb et al., 2020; Schmidt and Nüsser 2017), and together with the rise in temperature the impact will be comparatively higher on these glaciers. It is evident that the glacierised region around Leh is losing mass at a higher pace despite being in a higher altitude region between

Karakoram and other western Himalayan region. The higher retreat can be due to the presence of smaller glaciers in high numbers in Ladakh (Schmidt and Nüsser, 2017). These glaciers are more prone to rise in temperature and decline in solid precipitation due to their short response time, and they are most probably vulnerable to local climatic variations. Leh showed an increment of 0.04, 0.05 and 0.03 ºC/year in annual, JJAS and winter temperature, respectively, at $p<0.05$ (95% percent confidence level) through Man-Kendal test and Sen's slope estimator (Sen, 1968). However, the trend estimated in precipitation is negative but not statistically significant to conclude any inferences from it (Table 2).

The decline of glaciers in such environment is of serious concern as it directly impacts livelihood, ecosystem and socio-economic dimensions of the region because of their higher dependency on glacier meltwater streams. The residents of the region have witnessed a decline in agricultural yields, the main driver of economic development of the region, due to a decrease in water resources (Barrett and Bosak 2018). The water scarcity together with the recent boom in tourism activity (tourism footprint in Leh was 327,366 in 2018, a number that is more than the entire population of Ladakh) has led to a shift in livelihood from agriculture to other commercial activities (Müller et al. 2020), though even the latter relies heavily on water resources. To cope with water scarcity, some people of Ladakh have developed new water management techniques, commonly known as 'ice reservoirs' or 'ice stupas', to supplement agricultural activities (Nüsser, et al., 2019a,b).

4.1.2. Overall changes in Vegetation, built-up areas and lakes

Vegetation cover of within the village vicinity of a catchment was analysed in this study. Two entire glacier catchments of Kang Yatze region were also excluded from this analysis because no settlement exist in those remote catchments. Vegetation cover of overall study area is presented in Figure 5, 6, 7 and 8 along with the % change in 49 years. Four villages namely Chuchot, Stakna, Changa and Hemis are also included in the Stok region because they are partially fed by the meltwater coming from the Stok range. However, Hemis village is the only village in this study which is not fed by any glacier. The source of water for Hemis village is snowmelt and most probably springs within the catchment as the catchment does not have any glacier but comprise one of the oldest Monastery (Hemis monastery), village and vegetation.

Stok region consists of several villages in which Rumbak, Stok, Matoo, Martselang and Shang are completely fed by the glaciers of this region. Whereas, all the villages in Kang Yatze region i.e., Upshi, Miru, Lato, Gya, Sa-Soma and Rumtse are entirely fed by the glaciers of Kang Yatze region. In 1969, the vegetation area was found to be 17.2 and 2.8 km^2 in Stok and Kang Yatze region, respectively. Whereas, vegetation cover decreased over time in Stok region as a whole to 14 km^2 and increased in Kang Yatze region to 3.15 km^2. However, in few villages of Stok and Kang Yatze region, vegetation increased significantly. These significant changes are discussed in the village-level section (Section 4.2). The change observed over 49 years period was found to be -3.2 and 0.34 km^2 equivalent to -18.4 (-0.38 %/year) and 12.1 % (0.25 %/year) in Stok and Kang Yatze regions, respectively.

Overall, the vegetation cover decreased in the study area from 20.1 km^2 in 1969 to 17.2 km^2 in 2018. The total change found was -2.8 km^2 equivalent to -14.1 % (-0.29 %/year) in the entire study area in 49-year period (1969-2018). It should be noted that both the images (Corona and PlanetScope) used in this study are from summer pre-harvesting period to achieve minimum uncertainty. It is also possible that during these particular years (1969 or 2018) the harvest was good due to plenty of water or farming was abandoned due to lack of water, disaster or societal disputes thus raising the level of uncertainty in estimating the actual scenario. We made every possible effort to avoid such issues, and consulted Google Earth temporal image collections and other cloud free PlanetScope imageries of immediate years.

Built-up sites of the Stok and Kang Yatze regions increased from 0.61 and 0.15 km^2 in 1969 to 2.27 and 0.3 km^2 in 2018, with a change in 1.66 and 0.15 km^2 equivalent to 272 % (5.6 %/year) and 100% (2.1 %/year), respectively. Increase in built-up areas are directly associated with the increase in connectivity of the region. The road network in this region increased significantly with an increase from 81 and 61 km in 1969 to 250 and 105 km in 2018 in Stok and Kang Yatze region, respectively. The rise in road network was found to be 169 km (209 % at 4.3 %/year) and 44 km (72 % at 1.5 %/year) in Stok and Kang Yatze region, respectively. A comparatively less change in road network in Kang Yatze region was because all of these villages lie directly on the Leh-Manali highway and majority of the road remained same over these years except some link roads within these narrow villages.

The villages of Stok region are mostly away from major highways and thus multiple roads linking these villages were made. The mining activity (of gravel for constructions) within the study area are entirely situated in Stok region’s alluvial fan, thus giving rise to Built-up area and road network. Villages which were inaccessible for vehicular activity in 1969 are now accessible in 2018. Overall, an increase of 1.81 km^2 (238 % at 4.9 %/year) and 213 km (150 % at 3.1 %/year) of built-up area and road network was observed in the entire study area, respectively. Figure 5, 6, 7 and 8 presents the built-up area and % change over 49-year period between 1969 and 2018. Local population in the study area has grown more than double its size in 50 years at a rate of 2.3 %/year. This has led to an increase in built-up activities in the region. Also, the booming tourism industry with a 600+ fold in tourism footprint (Dame et al., 2019; Müller et al., 2020) over the years has initiated over exploitation of natural resources and unplanned urbanisation. The easy money in this industry has caused a shift in local economy from agriculture to tourism thus rendering the once cultivable land more prone to degradation and desertification.

Number of lakes increased from 15 lakes (2 in Stok and 13 in Kang Yatze region) in 1969 to 36 lakes (5 in Stok and 31 in Kang Yatze region) in 2018. Total lake area of Stok and Kang Yatze regions changed from 0.009 and 0.24 km^2 in 1969 to 0.02 and 0.52 km^2 in 2018, respectively. Figure 1, 2, 3 and 5 presents the lake location, area and % change in area in 49 years. Overall, change in lake area of the study area was found to be 0.3 km^2 equivalent to 122 % at a rate of 2.5 %/year. Identification of higher altitude lakes formed due to glacial retreat or moraine dammed lake are extremely important in this age when glacial lake outburst floods (GLOFs) are on the rise. GLOFs alone can be devastating especially when unplanned urbanisation in the downstream valleys is happening. Flash flood of Kedernath in 2013 and GLOF of Gya valley (Kang Yatze region) in 2014 (Schmidt et al., 2020; Majeed et al., 2021) are some of the few examples of such events.

4.2. Village level change in key environmental parameters

Regional level change of key environmental parameters, already discussed in previous sections, was not sufficient to explain the changes in detail. Therefore, we have also analysed the changes at village-scale. Tuchik, a catchment between Matoo and Martselang catchment, constitute insignificant amount of vegetation cover and no population or settlement area. Though, it is not a village but understanding this catchment is important from a glaciological perspective. This catchment holds only one glacier of Stok region with an area of 0.12 km^2 (2019) and lost half of its area (0.12 km^2, 1 %/year) in last 50 years (1969-2019).

Martselang on the other hand also showed similar but comparatively lower change in total area loss of 38% (0.68 km^2, 0.8 %/year) followed by Upshi, Matoo and Rumbak catchment with 19 (8.04 km^2, 0.38 %/year), 18.9 (0.93 km^2, 0.38 %/year) and 17% (0.38 km^2, 0.34 %/year) loss in total glacierised area in 50-year period, respectively. The common element between glaciers of Tuchik and Martselang catchment is the glacier size i.e., very small (~0.2 km^2), therefore the results indicate that glaciers of smaller sizes are more prone to retreat as compared to glaciers with a higher surface area. A small change in equilibrium line altitude or snow line altitude can expose these small glaciers entirely to melting thus losing a relatively higher surface area over time. Whereas glaciers of Stok and Sku-Markha catchment lost comparatively least relative glacierised area of 11.7 % (0.46 km^2, 0.23 %/year) and 11.4 % (3.48 km^2, 0.23 %/year), respectively. Since, the volume of glacier is related to the glacier area, therefore change in glacier volume is expected to follow the similar trend over 50-year period. The total volume change was found to be -38%, -15%, -15%, -21%, -25%, -15% and -12% in Tuchik, Rumbak, Stok, Matoo, Martselang, Upshi and Sku-Markha village catchments, respectively.

Built-up change was found to be inversely proportional to the vegetation of the village. Highest increase in built-up area was found in Stok village (688%) followed by Changa (247%), Chuchot (246%), Matoo (225%) and Hemis (205%). The nearly seven-fold rise in built-up area of Stok village is because of the seven-mining activity within the vicinity of village area. Road network in the vicinity of Stok village also increased significantly (380%) and is the highest among all the villages of the study area. Road network of Martselang also increased significantly (368%) followed by Matoo (253%), Changa (141%) and Chuchot (111%). Whereas, comparatively lowest increase in built-up area was found in Sku-Markha, Upshi, and Stakna with 62%, 122% and 134 % increase over 50-year period, respectively. Road network in some of these villages are also lowest among the study area with 8% and 28% in Upshi and Stakna. One of the main reasons for such low built-up area and road network is because of the two agricultural farms (one in each Stakna and Upshi) established in recent times (2005), a result of Igu-Phey canal which turned these barren lands into an irrigated farm (GJK, 2011; Nüsser et al 2012).

Vegetation of Upshi (48%), Changa (87%) and Rumbak (29.4%) increased whereas a decrease in vegetation was observed in other villages over 40-year period. Increase in vegetation of Upshi and Changa is the outcome of Igu-Phey canal which gave these barren lands an extra source of water for irrigation. Our results are in agreement with GJK, 2011 and Nüsser et al 2012. The barren land around Stakna has also been turned into a full-fledged agricultural and animal farm and expected to grow in coming years. Construction of such canals needs to be undertaken to supply water to those regions which has the potential for agricultural activity to increase food production of the region. Increase in built-up area and road network and decrease in vegetation is directly linked to the increase in population. Highest population growth was seen in Chuchot, Changa, Stok and Matoo with an increase of 158%, 132%, 112% and 72% in last 50 years (1971-2021). Whereas lowest growth in population was observed in Hemis, Rumbak and Sku-Markha with 33%, 38% and 53%, respectively. Figure 8 presents the change in all the key environmental parameters at a village level between 1969 and 2021.

5. Conclusion

In this study we analysed key environmental parameters including area and volume of 136 glaciers, built-up and vegetation of 13 villages, area of 36 lakes and demography of 13 major villages around Leh between 1969 and 2021. The area change of glaciers was obtained using freely available Corona and Landsat imageries with additional aid from PlanetScope image and Google Earth. A comparatively higher retreat (~19 at 0.38 %/year) in the glacierised area was found in 50 years as compared to the adjacent region of Shayok and Suru. The retreat was even higher (~35-50%) in very small glaciers of area ~0.02 km^2. Volume of glaciers also decreased over time with a reduction of 0.42 km^3 equivalent to ~13% (0.8 %/year) of the volume in 16-year period. At present, the study area holds 2.5 Gt of water in these glaciers.

A decrease (-5 to -58%) in vegetation was found in majority of the villages except Rumbak (29%), Upshi (48%) and Changa (87%) where vegetation significantly increased over 49-year period. The 43 km long Igu-Phey canal played a major role in such increase in vegetation. Increase in built-up area (688%) and road network (380%) was found highest in Stok village due to seven gravel mining activity in the area whereas, other village witnessed comparatively lower increase in built-up area (63-275%) and road network (8-368%). An inverse relationship was found between % change of vegetation and % change of Built-up area. Increase in population growth percentage was also found highest in Stok (112%), Changa (132%) and Chuchot (157%) whereas in other villages the population growth was comparatively lower (32-72%). One of the major reasons for higher increase in built-up areas and road network, and a decrease in vegetation is most probably the tourism industry as tourist footprint in last 44 years was 620 times (527 in 1974 to 327366 tourists in 2018). Another factor for such change can also be attributed to government and defence related activities which is expected to grow in coming years due to redesignation of Ladakh as a Union Territory. Formation of new lakes were also observed in 49 years. Number of lakes increased from 15 to 36 with an increase in area from 0.25 km^2 to 0.55 km^2 equivalent to 122% change in lake area between 1969 and 2018.

While research and policy focus is slowly falling on Leh City and its vicinity, our study proves that environmental changes are happening at a higher rate in rural regions around Leh. A proper assessment and a detailed future planning are very much required in rural regions as well. Systematically documenting these changes using multisource datasets for a larger region can provide more holistic picture of the effects which these mountains are experiencing under the contemporary climate change and demographic shifts.

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7. Data availability statement

The data that support the findings of this study are available on request from the lead author. The data belongs to the lead author's PhD program and cannot be made public for now.

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Table 1: Presents the data used in the present study.

	Data	Scene ID	Years	Spatial res.	Use
1	Landsat TM Landsat TM Landsat TM Landsat OLI	LT05_L1TP_147037_19910828_20170126_01_T1 LT05_L1TP_147037_19980916_20161222_01_T1 LT05_L1TP_147037_20100917_20161013_01_T1 LC08_L1TP_147037_20190910_20190917_01_T1	1991, 1998, 2010, 2019	30m	Glacier mapping
2	Corona	DS1107-1104DA015 (30 July) DS1107-1104DA016 (30 July) DS1107-1104DA017 (30 July) DS1107-1104DA018 (30 July) DS1107-1104DA019 (30 July) DS1107-1104DA020 (30 July)	1969	3m	Glacier, vegetation, built-up and water body mapping
3	ASTER DEM	AST14DMO.003:2025691837 (08 September) AST14DMO.003:2025691835 (08 September) AST14DMO.003:2404575282 (20 September) AST14DMO.003:2404575284 (20 September)	2004 2004 2020 2020	30m	Glacier thickness estimation, catchment delineation.
4	PlanetScope	20180829_045714_0f2a, 20180829_045715_0f2a, 20180829_045716_0f2a, 20180829_045717_0f2a, 20180829_045718_0f2a, 20180829_045719_0f2a, 20180829_045720_0f2a, 20180829_045721_0f2a, 20180829_045722_0f2a, 20180829_045723_0f2a, 20180829_045724_0f2a, 20180829_045725_0f2a, 20180829_045726_0f2a, 20180829_050228_103b, 20180829_050229_103b, 20180829_050230_103b, 20180829_050231_103b, 20180829_050232_103b, 20180829_050233_103b, 20180829_050308_103d, 20180829_050309_103d, 20180829_050310_103d, 20180829_050311_103d, 20180829_050312_103d, 20180829_050313_103d, 20180829_050314_103d, 20180829_050315_103d, 20180829_050316_103d, 20180829_050317_103d, 20180829_050318_103d, 20180829_050319_103d, 20180829_050420_0f17, 20180829_050421_0f17, 20180829_050422_0f17, 20180829_050424_0f17, 20180829_050425_0f17, 20180829_050426_0f17, 20180829_050427_0f17, 20180829_050428_0f17, 20180829_050429_0f17, 20180829_050532_0f28, 20180829_050533_0f28, 20180829_050534_0f28, 20180829_050535_0f28	2018	3m	Glacier, vegetation, built-up and water body mapping
5	ERA5 data	ERA5 hourly data on single levels from 1979 to 2019. DOI: 10.24381/cds.adbb2d47	1979-2019	0.25º	Climate analysis
6	Census data	Census report of 1971, 1981, 2001 and 2011.	1971, 1981, 2001, 2011	10 year	Demographic change

Table 2: Results of Mann -Kendall and Sen's slope estimator for annual, JJAS and winter temperature and precipitation.

	ANNUAL				**JJAS**				**WINTER**			
ERA5 Grid points	Mann-Kendall Significance (p)	Sens Slope (β)	Long-term Mean (ºC or mm)	Change (ºC or mm)	Mann-Kendall Significance (p)	Sens Slope (β)	Long-term Mean (ºC or mm)	Change ºC or mm	Mann-Kendall Significance (p)	Sens Slope (β)	Long-term Mean (ºC or mm)	Change ºC or mm
Leh Temperature	**0.01**	**0.04**	**7.65**	**0.21**	**0.01**	**0.05**	**18.67**	**0.11**	**0.05**	**0.03**	**-0.45**	**-2.73**
Leh Precipitation	0.4	-0.33	58.12	-0.23	0.6	-0.1	27.65	-0.15	0.9	0.001	19.27	0.00

Table 3: Uncertainty in glacierised area for different years through buffer based assessment.

Region	**1969**	**1991**	**1998**	**2010**	**2019**
	km^2	*km^2*	*km^2*	*km^2*	*km^2*
Stok	±0.1 (0.8%)	±0.6 (6.1%)	±0.6 (6.1%)	±0.6 (6.6%)	±0.6 (7.1%)
Kang Yatze	±0.5 (0.7%)	±3.4 (4.9%)	±3.3 (5.0%)	±3.2 (5.4%)	±3.1 (5.6%)
All	±0.6 (0.5%)	±4 (3.9%)	±3.9 (4.0%)	±3.8 (4.1%)	±3.7 (4.2%)

Table 4: Estimated uncertainty in mean thickness (m) and total ice volumes (km^3) in Glabtop2, slope dependent and area scaling methods.

Uncertainties in glabtop2 and slope dependent methods				
REGION	**2004**		**2020**	
	Thickness	**Volume**	**Thickness**	**Volume**
	m	**km^3**	**m**	**km^3**
Stok	±4.6 (±23.7%)	±0.002 (±23.8%)	±3.8 (±22.6%)	±0.002 (±22.6%)
Kang Yatze	±6.4 (±25.5%)	±0.009 (±25.7%)	±4.9 (±23%)	±0.006 (±23.1%)
All	±6 (±25.1%)	±0.007 (±25.3%)	±4.63 (±23%)	±0.005 (±22.9%)

Uncertainties in area scaling method								
REGION	**2004**				**2020**			
	Glacier area +5%		*Glacier area -5%*		*Glacier area +5%*		*Glacier area -5%*	
	Chen and Ohmura (1990)	**Bahr et al., (1997)**	**Chen and Ohmura (1990)**	**Bahr et al., (1997)**	**Chen and Ohmura (1990)**	**Bahr et al., (1997)**	**Chen and Ohmura (1990)**	**Bahr et al., (1997)**
	km^3 (Difference)	*km^3 (Difference)*	*km^3 (Difference)*	*km^3 (Difference)*	*km^3 (Difference)*	*km^3 (Difference)*	*km^3 (Difference)*	*km^3 (Difference)*
Stok	0.31 (+6.9%)	0.35 (+6.1%)	0.27 (-6.9%)	0.31 (-6.1%)	0.27 (+8.0%)	0.3 (+7.1%)	0.23 (-8.0%)	0.26 (-7.1%)
Kang Yatze	3.08 (+6.9%)	3.55 (+6.9%)	2.69 (-6.6%)	3.09 (-6.9%)	2.85 (+6.7%)	3.29 (+7.2%)	2.5 (-6.4%)	2.87 (-6.5%)
All	3.39 (+6.9%)	3.9 (+6.8%)	2.96 (-6.6%)	3.4 (-6.8%)	3.12 (+6.8%)	3.59 (+7.2%)	2.73 (-6.5%)	3.13 (-6.6%)

Table 5: Uncertainty in lake and build up area, and accuracy assessment for vegetation area.

Uncertainties in the lake area								
REGION	**Analyst A**		**Analyst B**		**Analyst C**		**±Uncertainty (%)**	
	1969 (km2)	***2018 (km2)***	***1969 (km2)***	***2018 (km2)***	***1969 (km2)***	***2018 (km2)***	***1969***	***2018***
Stok Region	0.009	0.022	0.009	0.021	0.008	0.023	2.35	2.61
Kang Yatze Region	0.237	0.524	0.231	0.511	0.239	0.523	1.33	1.17
All	0.246	0.546	0.240	0.532	0.247	0.546	1.21	1.22
Uncertainties in the build-up area								
SAMPLE VILLAGE	***1969 (m2)***	***2018 (m2)***	***1969 (m2)***	***2018 (m2)***	***1969 (m2)***	***2018 (m2)***	***1969***	***2018***
Chuchot Village	0.280	0.969	0.264	0.939	0.273	0.989	2.28	2.12
Stok Village	0.062	0.492	0.061	0.517	0.064	0.501	1.91	2.08
All	0.342	1.461	0.325	1.456	0.337	1.490	2.06	1.04
Accutacy assessment for the vegetation area								
REGION	***1969***				***2018***			
	Overall Accuracy		***Kappa Cofficient***		***Overall Accuracy***		***Kappa Cofficient***	
Stok	79%		0.72		92%		0.9	
Kang Yatze	74%		0.6		89%		0.86	
All	77%		0.66		91%		0.88	

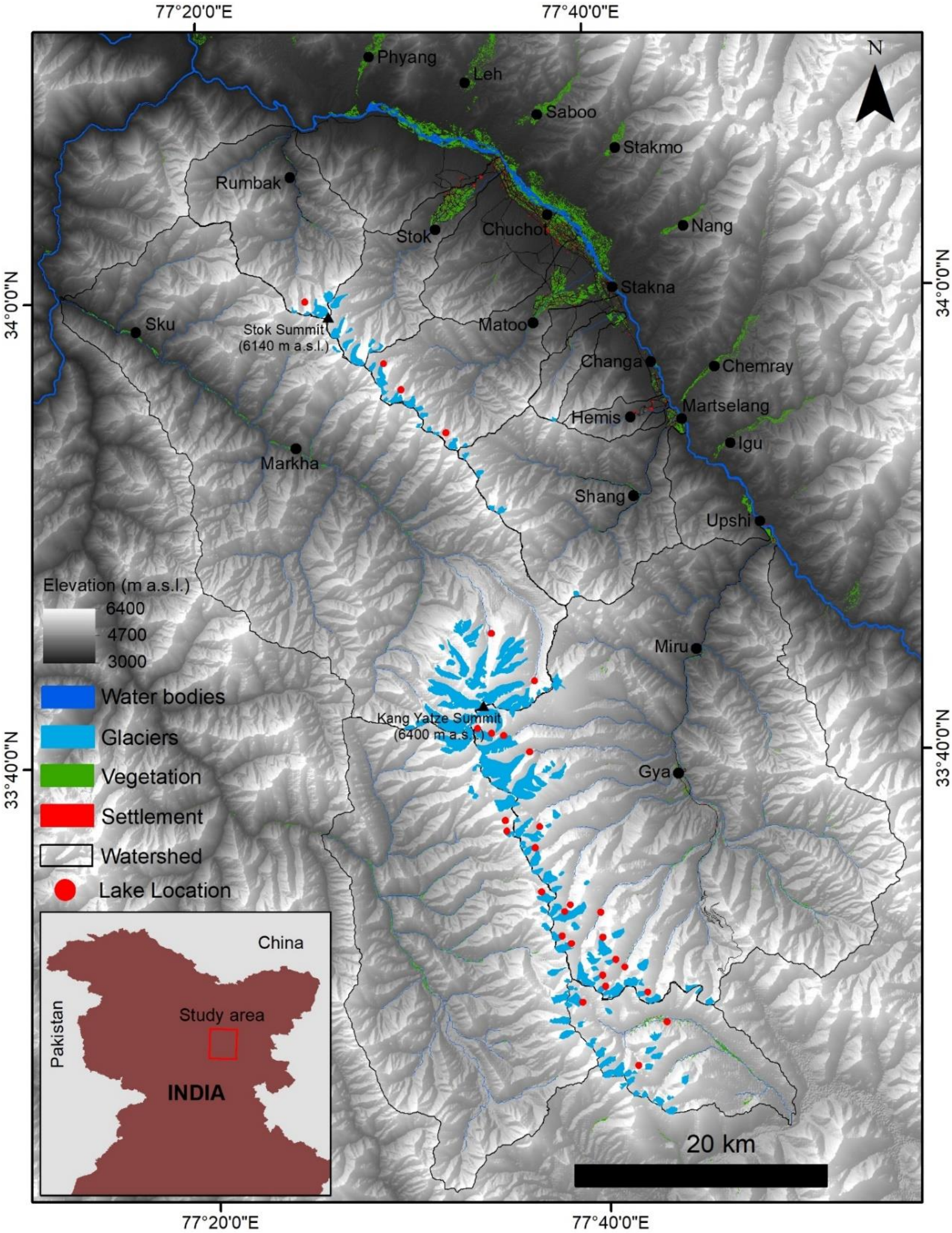

Figure 1: Location map of the study area presenting all the mapped key environmental parameters. Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model (ASTER DEM) has been used in the background to provide the topographic details. The inset map highlights the contextual location of study area in North India.

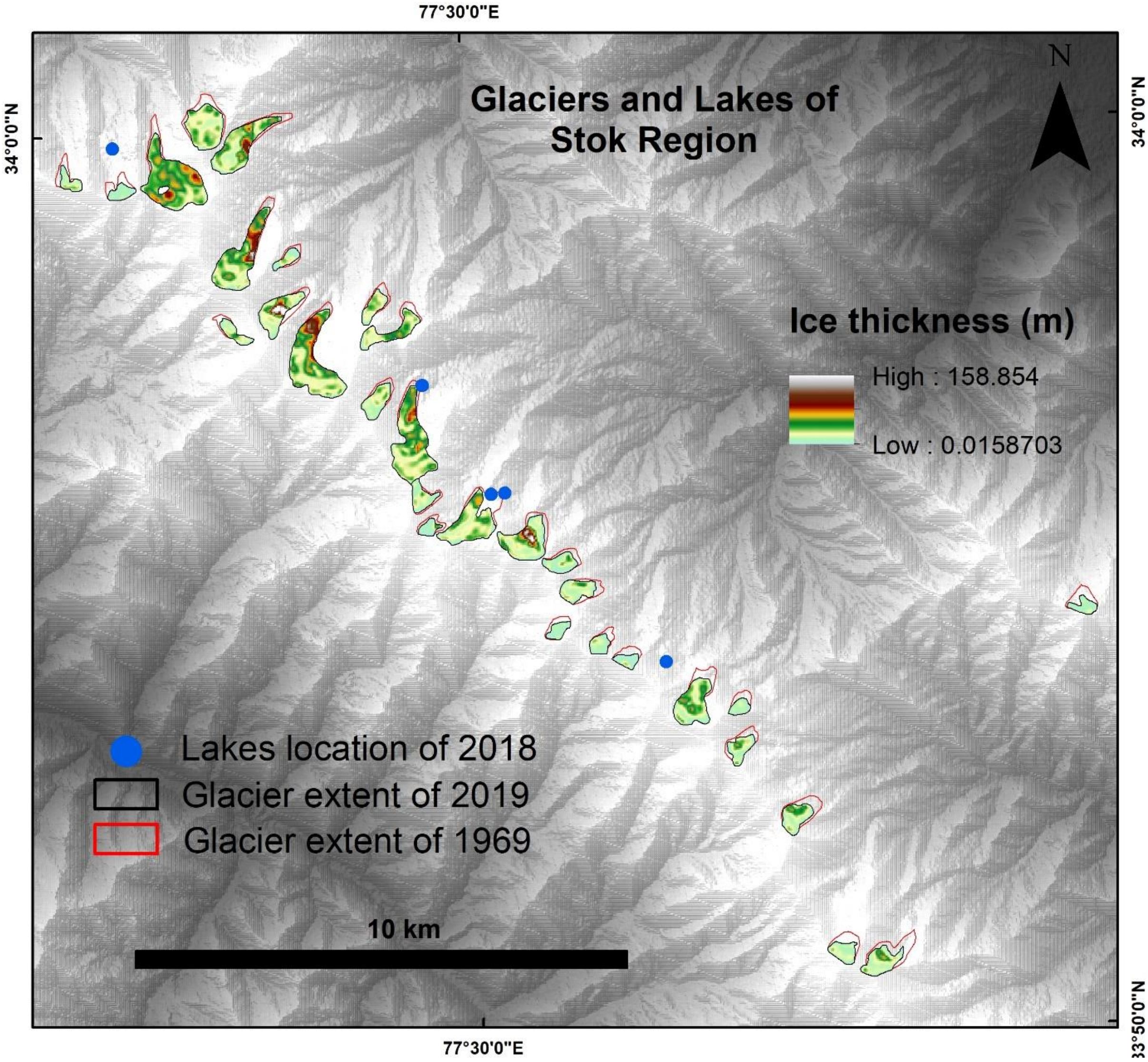

Figure 2: Presents the glacier outlines of 1969 and 2019, glacier thickness of 2020 and location of lakes in Stok region

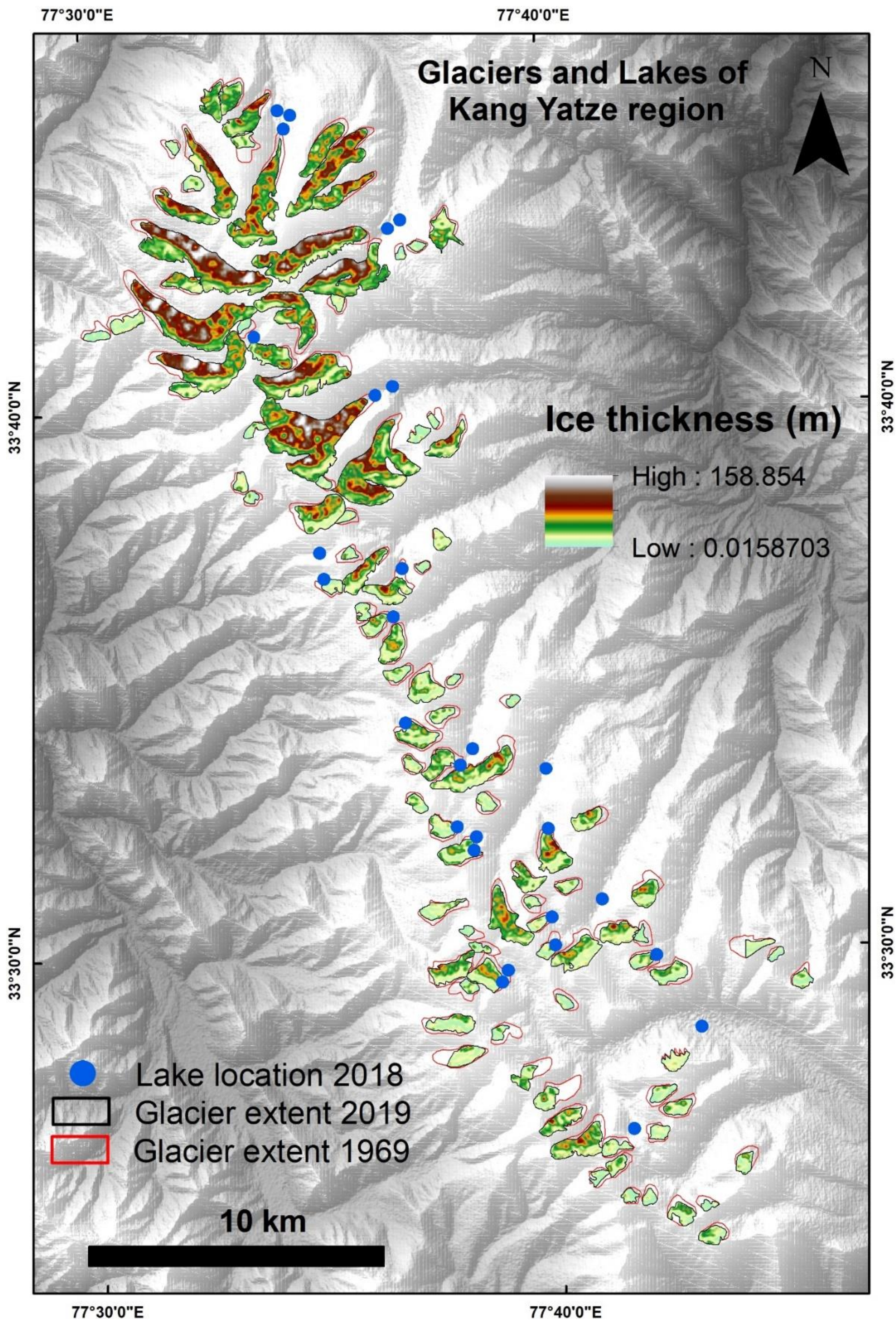

Figure 3: Presents the glacier outlines of 1969 and 2019, glacier thickness of 2020 and location of lakes in Kang Yatze region

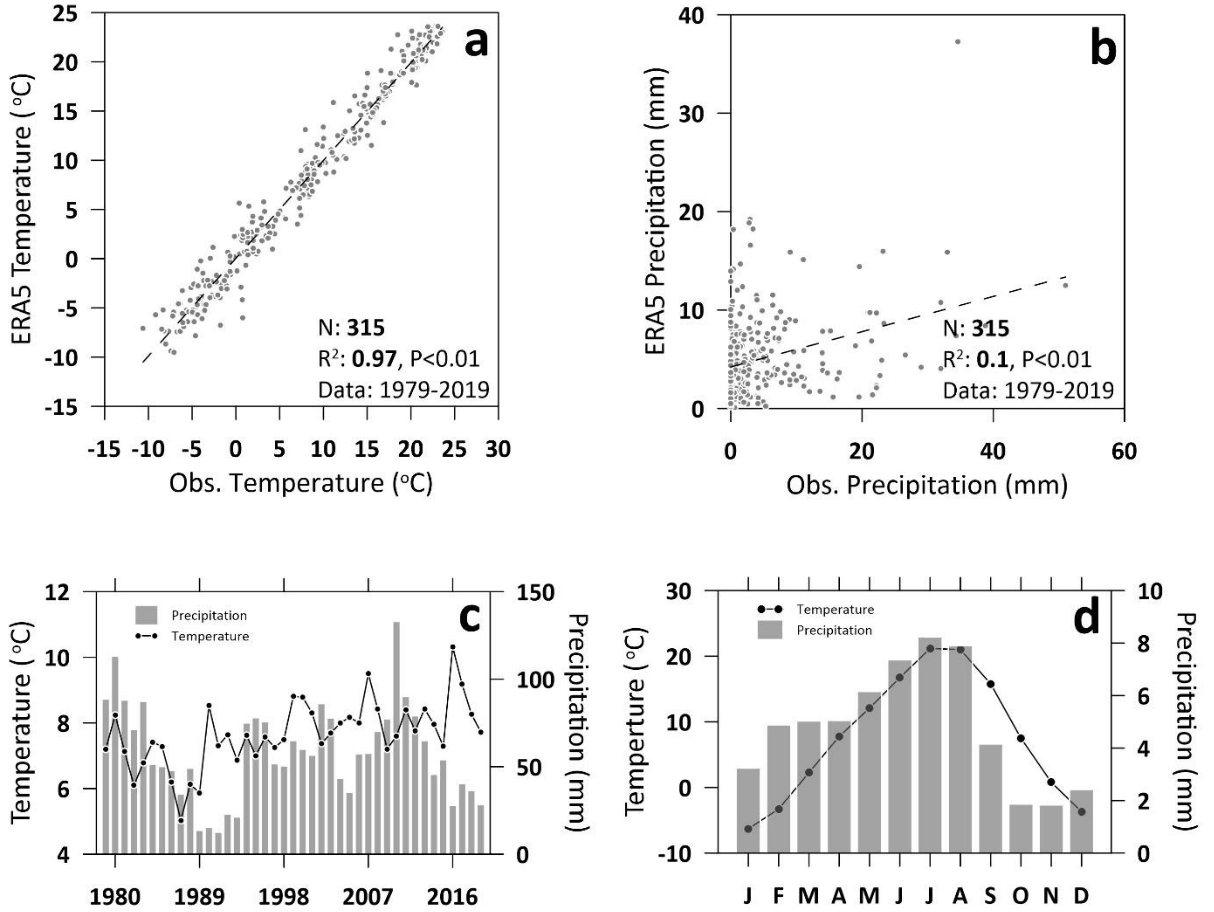

Figure 4: ERA5 bias corrected temperature and precipitation of Leh grid from 1979 to 2019. a and b are the correlation between observed and ERA5 reanalysis temperature and precipitation. c and d are annual and monthly temperature and precipitation.

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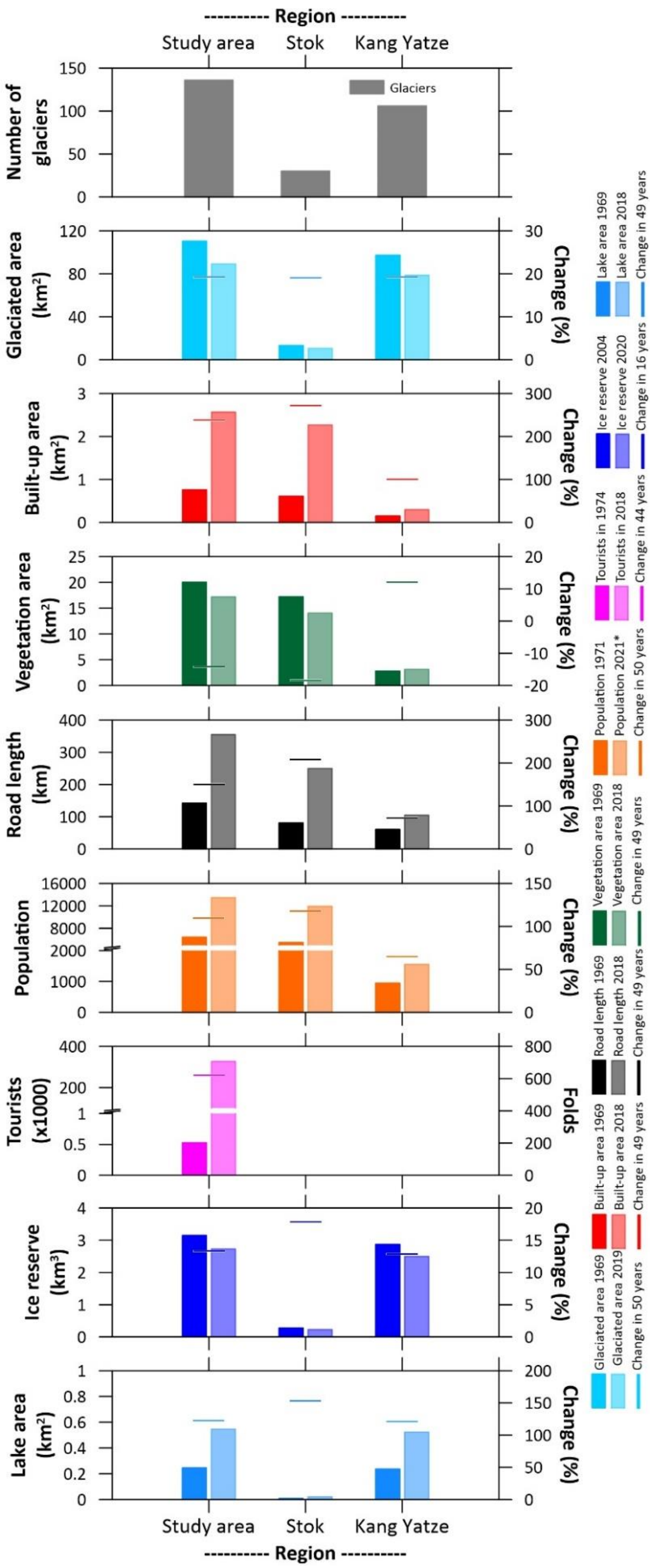
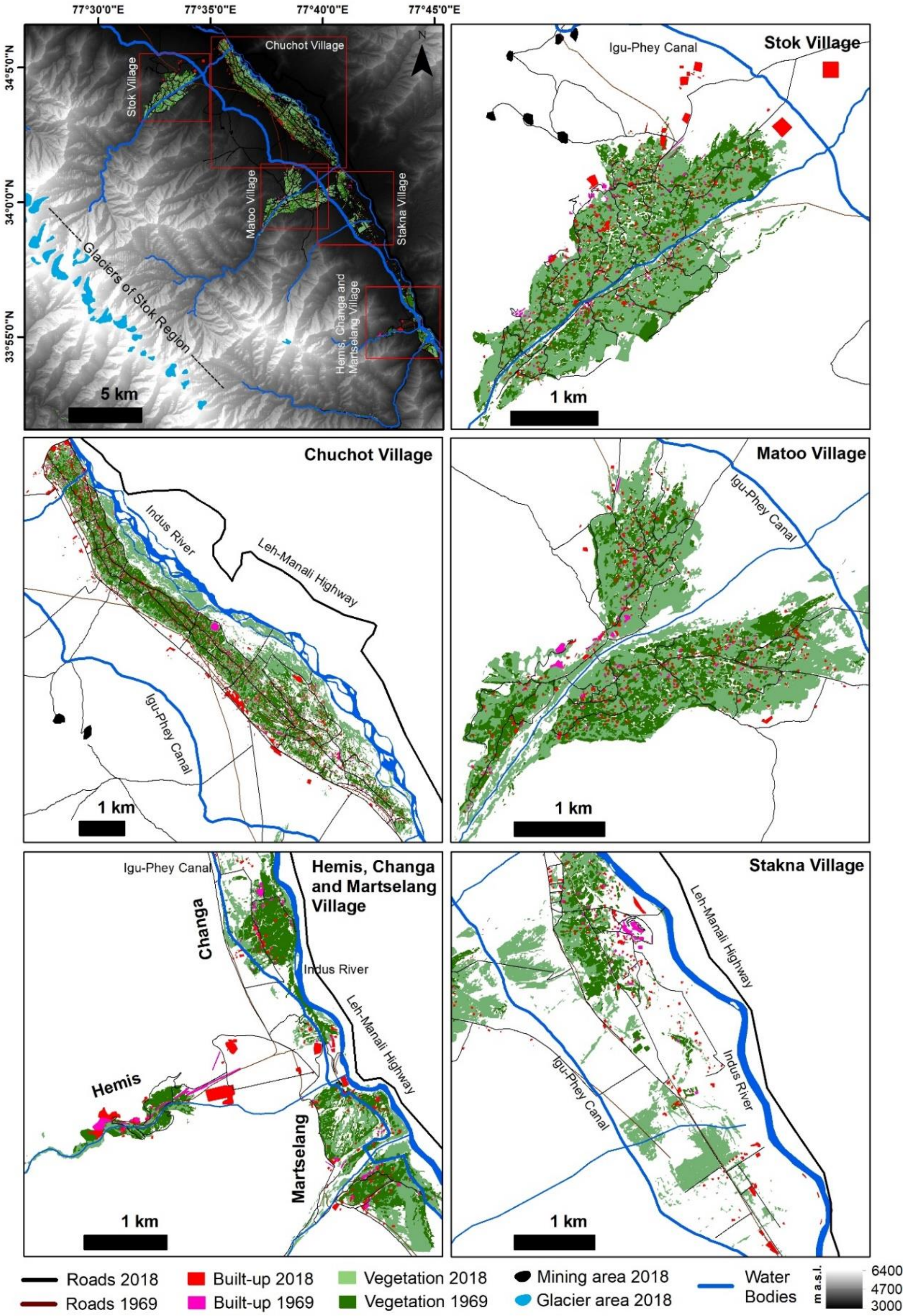


807 **Figure 5**: Total change of key environmental parameters over the years in the study area, Stok
808 and Kang Yatze regions



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810 **Figure 6**: Presents Vegetation, Built-up and Waterbodies map over the years in Stok region.

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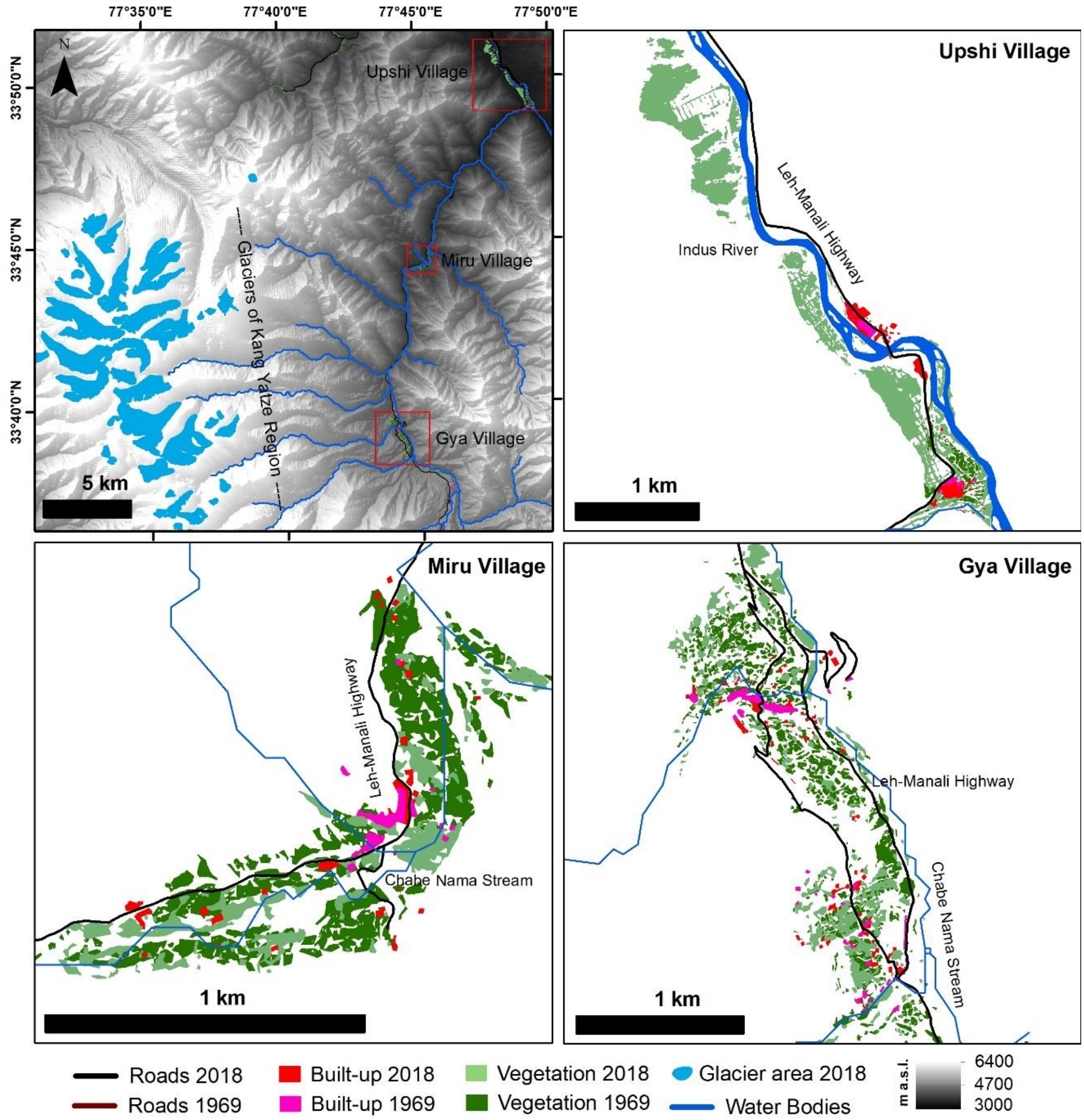

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813 **Figure 7**: Presents Vegetation, Built-up and Waterbodies map over the years in Kang Yatze region

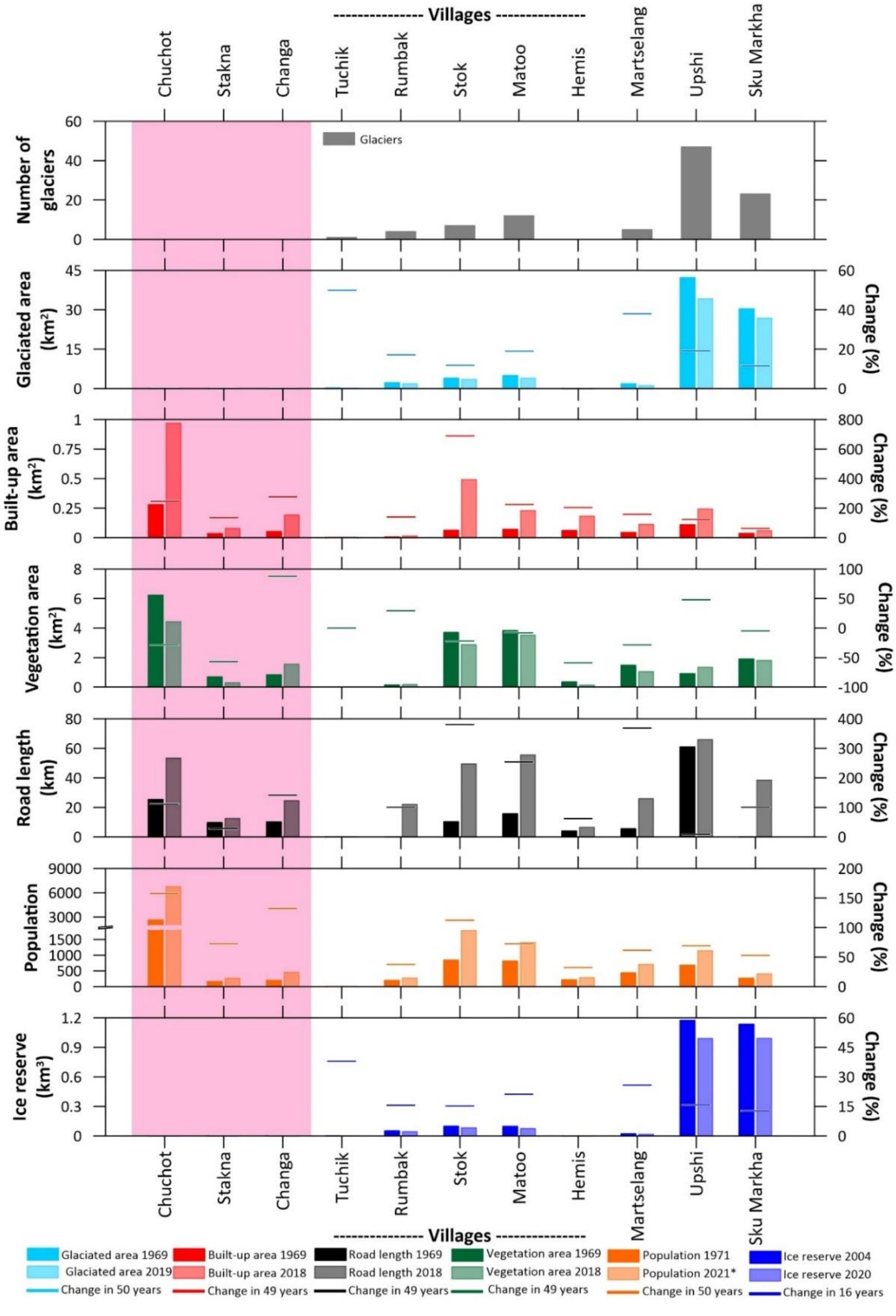

Figure 8: Village level change of key environmental parameters over the years in the study area. The section with pink background represents the Indus-fed villages

Figure 9: Location map of the study area presenting all the mapped key environmental parameters. Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model (ASTER DEM) has been used in the background to provide the topographic details. The inset map highlights the contextual location of study area in North India.

Figure 10: Presents the glacier outlines of 1969 and 2019, glacier thickness of 2020 and location of lakes in Stok region

Figure 11: Presents the glacier outlines of 1969 and 2019, glacier thickness of 2020 and location of lakes in Kang Yatze region

Figure 12: ERA5 bias corrected temperature and precipitation of Leh grid from 1979 to 2019. a and b are the correlation between observed and ERA5 reanalysis temperature and precipitation. c and d are annual and monthly temperature and precipitation.

Figure 13: Total change of key environmental parameters over the years in the study area, Stok and Kang Yatze regions

Figure 14: Presents Vegetation, Built-up and Waterbodies map over the years in Stok region.

Figure 15: Presents Vegetation, Built-up and Waterbodies map over the years in Kang Yatze region

Figure 16: Village level change of key environmental parameters over the years in the study area. The section with pink background represents the Indus-fed villages