Identifying potential hotspots of land use/land cover change in the last 3 decades, Uttarakhand, NW Himalaya

Shravi Agarwal[1], Vipin Kumar[1*], Sanjeev Kumar[1], Yaspal Sundriyal[1], Dhirendra Singh Bagri[1], Neha Chauhan[1], Sameeksha Kaushik[1], Firoz Khan[1], Naresh Rana[2]

[1]Department of Geology, HNB Garhwal University, Srinagar, India
[2]Department of Geology, University of Delhi, Delhi, India

*Correspondence: v.chauhan777@gmail.com

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ABSTRACT

Uttarakhand region in the NW Himalaya has experienced two extreme climatic-geomorphic events within last 10 years that killed more than 6000 people. Though these events, like many others in the Himalaya, have been attributed to climate-change and anthropogenic disturbances, identification of potential hotspots of land use/land cover change is rarely attempted to make future inferences for disaster risk reduction. An evaluation of spatio-temporal changes in land use/land cover can be used to identify such hotspots. Therefore, we analysed the spatio-temporal changes in a climatically sensitive and natural disaster-prone area (~28856 km^2) of Uttarakhand (NW Himalaya), India, by comparing the satellite data of years 1991-2020 for ten land use/land cover elements to track the spatio-temporal changes over these years. Results revealed the formation of two hotspots exhibiting relatively more changes in land use/land cover pattern. Though the anthropogenic influence is observed in both hotspots, the influence of spatio-temporally changing climatic parametres is also noted. In view of frequent extreme climatic-geomorphic events, temporally increasing population and tourist pressure, and temporally changing climatic conditions, it is vital to identify hotspots having dominant changes in land use/land cover to understand the possible source of potential disasters.

Keywords: Land use/Land cover; Uttarakhand; Himalaya; Climate; Anthropogenic action.

1.0 INTRODUCTION

The present pattern of infrastructural development and subsequent population increase in the fragile ecosystem in mountain ranges have resulted in increased stress on environment in the form of land use/land cover changes (Paudel et al. 2016). The studies pertaining to the land use/land cover refer to extracting the information about physical characteristics of the earth surface features along with the patterns of their utilization in time and space (Rawat & Kumar, 2015). Change in the land use/land cover is the primary variable that affects a wide variety of socioeconomic, ecological, climatic, and hydrological systems (Sohl & Sohl, 2012). Recent studies have noted the effect of changing climate on the land use/land cover heterogeneities in the mountain systems and such heterogeneities have been observed to alter the physical/chemical/biological properties of land-surface; vegetation pattern, heat capacity, moisture supply, emissivity, and surface temperatures (Reid et al. 2000; Dirmeyer et al., 2010, Caballero et al., 2022).

One of the major causes of land use/land cover changes has been rapid population growth and infrastructural development that often lead to land degradation and deforestation (Verma et al., 2021). Himalaya, sustaining many variety of biodiversity and natural resources, has been subjected to rapid land use/land cover changes that might be main contributing factor of increased frequency of extreme events; landslide, floods, mudflows, avalanches, and associated chain of disasters in last decade killing more than 6000 people (Martha et al. 2015; Gupta et al. 2017; Gupta et al. 2018; Jamir et al. 2020; Kumar et al. 2021; Rana et al. 2021). Identification of potential hotspots of land use/land cover change has been used in many studies to understand the varied influence of climate and anthropogenic activities (Li et al. 2020; Fang et al. 2022). Similarly the identification of such hotspots can be crucial in Himalaya, particularly NW Himalaya to determine the regions having maximum changes and potential of future disasters.

The methods to evaluate the land use/land cover changes for different time periods have been either manual mapping or automatic/semi-automatic; supervised/unsupervised classification (Paudel et al. 2016). While the manual mapping of different classes of the land use/land cover is a time-consuming task, it ensures relatively more accuracy unlike automatic/semi-automatic, which requires detailed verification. The present study attempts to evaluate the land use/land cover changes during the years 1991-2020 in Uttarakhand, NW Himalaya (India). Though some studies have been attempted earlier to determine the land use/land cover changes in small regions of Uttarakhand (Rawat & Kumar, 2015; Rawat et al., 2012; Taloor et al., 2020; Tiwari, 2000), regional scale evaluation has rarely been performed. The findings of present study will be useful to determine the regions having relatively more land use/land cover changes and their possible causes in view of changing climate and anthropogenic pressure.

2.0 STUDY AREA

The study area covers five hilly districts i.e., Uttarkashi, Rudraprayag, Tehri, Chamoli and Pithoragarh in Uttarakhand (NW Himalaya), India (Fig.1). These districts covering a total area of ~28856 km^2 has varying topography with elevation ranging between 330 m above msl and 7253 m above msl.

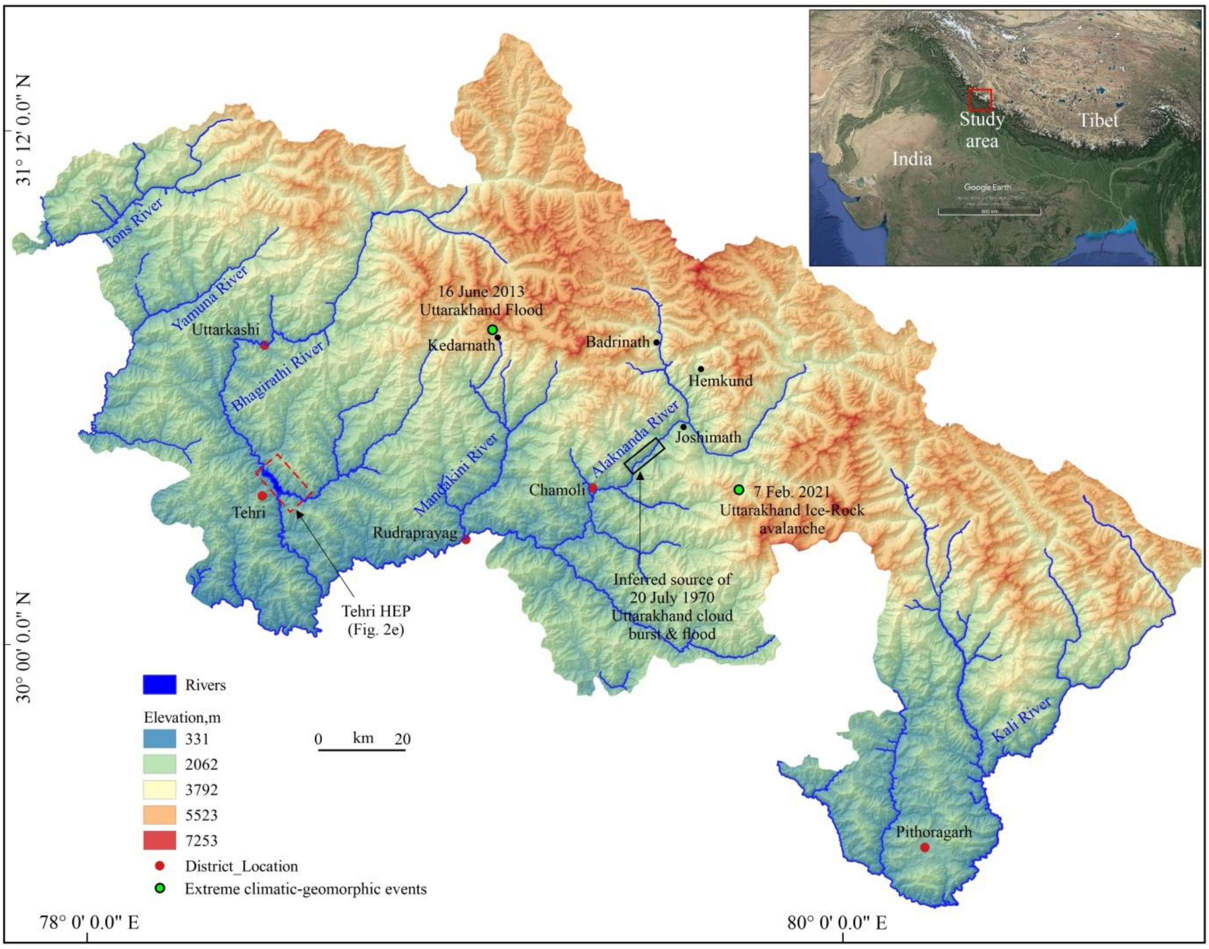

Fig. 1: Location map of the study area. Inset highlights the position of study area in the NW Himalaya. Elevation data source: ALOS PALSAR RTC © JAXA/METI, accessed through ASF DAAC, https://asf.alaska.edu, retrieved on 02/03/2022, DOI: 10.5067/Z97HFCNKR6VA. Location of extreme climatic-geomorphic events in the region; 20 July 1970, 16 June 2013, and 7 Feb. 2021 are also shown.

The study area comprises litho-units of Lesser Himalayan sedimentary, Lesser Himalayan meta-sediments (or Lesser Himalaya Crystalline), Higher Himalayan Crystallines, and Tethyan Sequence from south to north (Valdiya 1980; Vannay and Grasemann, 2001; Mukherjee et al. 2019). The major rivers draining through the study area are Tons, Yamuna, Bhagirathi, Alaknanda, and Kali. The varying topography and geographical position allow the study area to get subjected to spatio-temporally varying climate conditions, particularly precipitation, which it receives from two precipitation systems; Indian Summer Monsoon (ISM) and Westerly Disturbance (Benn and Owen, 1998; Singh and Mal, 2014; Dimri 2015). Notably, the terrain around Kedarnath-Badrinath comprises relatively higher topography in the study area and has been subjected to three extreme climatic-geomorphic events (20 July 1970, 16 June 2013, 7 Feb. 2021) and two of these three have occurred in last 10 years that killed more than 6000 people and resulted in a minimum loss of ~50 million USD (Rana et al. 2013; Martha et al. 2015; Houze Jr. 2017; Rana et al. 2021).

3.0 METHODOLOGY

Growing possibility of extreme climatic-geomorphic events (Xu et al. 2009; Shekhar et al. 2017) coupled with population increase in the study area at a decadal rate of 11.5 % (https://nhm.gov.in), land use/land cover might change drastically leading to various socio-economic challenges. The present study is an attempt to identify potential hotspots having relatively more land use/land cover changes during the years 1991-2020. The satellite images (Supplementary Table 1) were co-registered, stacked and mosaicked to map the land use /land cover features while maintaining a root mean square error (RMSE) of less than 1 pixel using ground control points (GCPs) in ERDAS Imagine 14 software. To have minimum snow cover and cloud free images, satellite images belonging to September (autumn season) were retrieved. These GCPs were collected during the field visits in years 2018-2021. Further, all images have been projected at Universal Transverse Mercator (UTM) geographic projection, WGS84 spheroid, and zone 44 North datum. Though the visual classifications of various land use/land cover (LU/LC) classes takes relatively more time than automatic classification, it provides relatively more accuracy. Based on the visual interpretations of tone and texture of the images, and the classification policy of National Remote Sensing Centre (ISRO, India) (https://www.nrsc.gov.in), study area was divided into following ten classes of the land use/land cover; Agriculture land, Built-up (rural/urban), Glaciated area, Grassland, Dense Forest, Moderately Dense Forest, Scrub Forest, Barren land (rocky/stony land), Scrubland (or Shrubland), and Waterbodies.

For better classification of various classes, different band combinations were used. Landsat image bands: 5, 4, 3 combinations provided a "natural-like" rendition to differentiate between glaciers and different LU/LC features, whereas bands: 4, 3, 2 were used where vegetation was bright red, and finally bands: 6, 4, 2 where water appeared dull blue. The geometrical information of the LU/LC classes were mapped using the polygon feature and were incorporated into the GIS domain to enable change analysis. Since the present study employs temporal datasets, mapping uncertainties were estimated by a comparison between known and mapped area. The uncertainties of 8.05% and 4.20% were noted between known distances/area (field measurement) and measured ones in the Landsat (spatial resolution 30 m) and LISS-IV (spatial resolution 5.8 m) imagery, respectively.

4.0 RESULTS AND DISCUSSION

The land use/land cover (LU/LC) layers were prepared for the years 1991, 2001, 2011, and 2020 and the total change in different LU/LC layers during the years 1991-2020 is shown in figures 2. The LU/LC of intermediate years, i.e., 2001 and 2011 is shown as supplementary Fig. 1. It is noted that during the years 1991-2020, the glaciated area, forest area (dense and moderately dense), grasslands, and agricultural land reduced, which contributed directly and/or indirectly to the increase of barren land, shrubland, forest scrub, water bodies, and built-up area (Fig. 2c-d). The LU/LC layers (or elements), which witnessed the decrease are as follows;

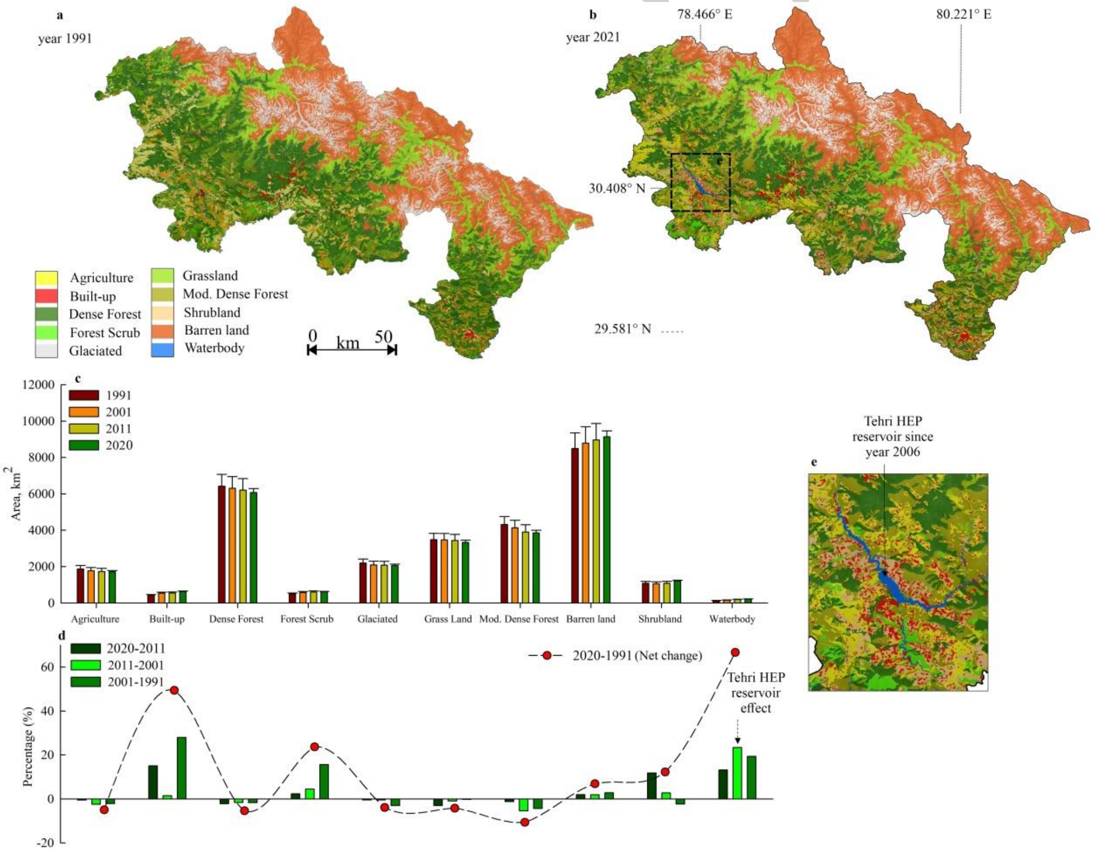

Fig. 2: Spatio-temporal variations in land use/land cover (LU/LC). (a) year 1991 LU/LC; (b) year 2020 LU/LC; (c) Area wise distribution of different LU/LC layers in year 1991, 2001, 2011, and 2020; (d) Relative increase (%) of different LU/LC layers in different decades; (e) Tehri HEP (Hydroelectric power) water reservoir.

Like other glaciers in different mountain ranges, most of the Himalayan glaciers have also showed general state of decline in the last few decades (Bhambri et al. 2011; Bolch et al., 2012, 2019). Out of 9775 glaciers in India, Uttarakhand region comprises 968 glaciers (Raina and Srivastava, 2008). We noted that the glaciated area in year 1991 was 2153±173 km^2 that decreased to 2069±86 km^2 in year 2020. This decrease, equivalent to ~3.9% (~84±10 km^2), mostly occurred during the years 1991-2001 followed by 2011-2020 (Fig. 2d). Relatively higher decrease is noted in the northern part (Kedarnath-Badrinath region) (Fig. 3a).

The glacial decrease in the Kedarnath and surrounding region might be attributed to the increase in surface radiative temperature and runoff during the years 1991-2021 (Fig. 4a-b). Generally, glaciated region represents relatively higher surface runoff owing to combined output of glacial melt and precipitation runoff. However, the temporal increase of surface runoff along with the increase in surface radiative temperature enhances the possibility of changing climate influence (Fig. 4c-d). Further, the power-law (R^2=0.7) of temperature and surface runoff showing rapid increase of surface runoff beyond a specific surface temperature strengthens the possibility of changing climate induced temperature rise and resultant enhanced runoff (Fig. 4e). Though anthropogenic factors in the form of growing human population and tourist influx in this region (Fig. 4f-h) might also contribute to the depleting trend of glaciated region, their exact role and mechanism is poorly understood so far. Notably, the surface radiative temperature might be 2°-6°C different from the aero-dynamic temperature of the region owing to unstable conditions at higher altitude and hence resultant moisture flux, affecting the snow/ice layer, might also be different (Sun and Mahrt, 1995). Though some studies have also noted the dimensional decrease in many individual glaciers in Uttarakhand, NW Himalaya (Dobhal et al., 2004, Nainwal et al., 2008; Bhambri et al. 2011; Kulkarni and Karyakarte 2014; Immerzeel et al., 2020), the regional pattern of such decrease is still less understood. Such dimensional reduction might have long term repercussions in the Himalaya in view of 1 º- 4 ºC predicted rise in the mean global surface temperature in the 21st century that might increase glacial surface runoff and subsequent expansion of glacial lakes (Scherler et al., 2011; IPCC, 2013; Immerzeel et al., 2020). Apart from the glaciated area, a net reduction in forest area is also noted.

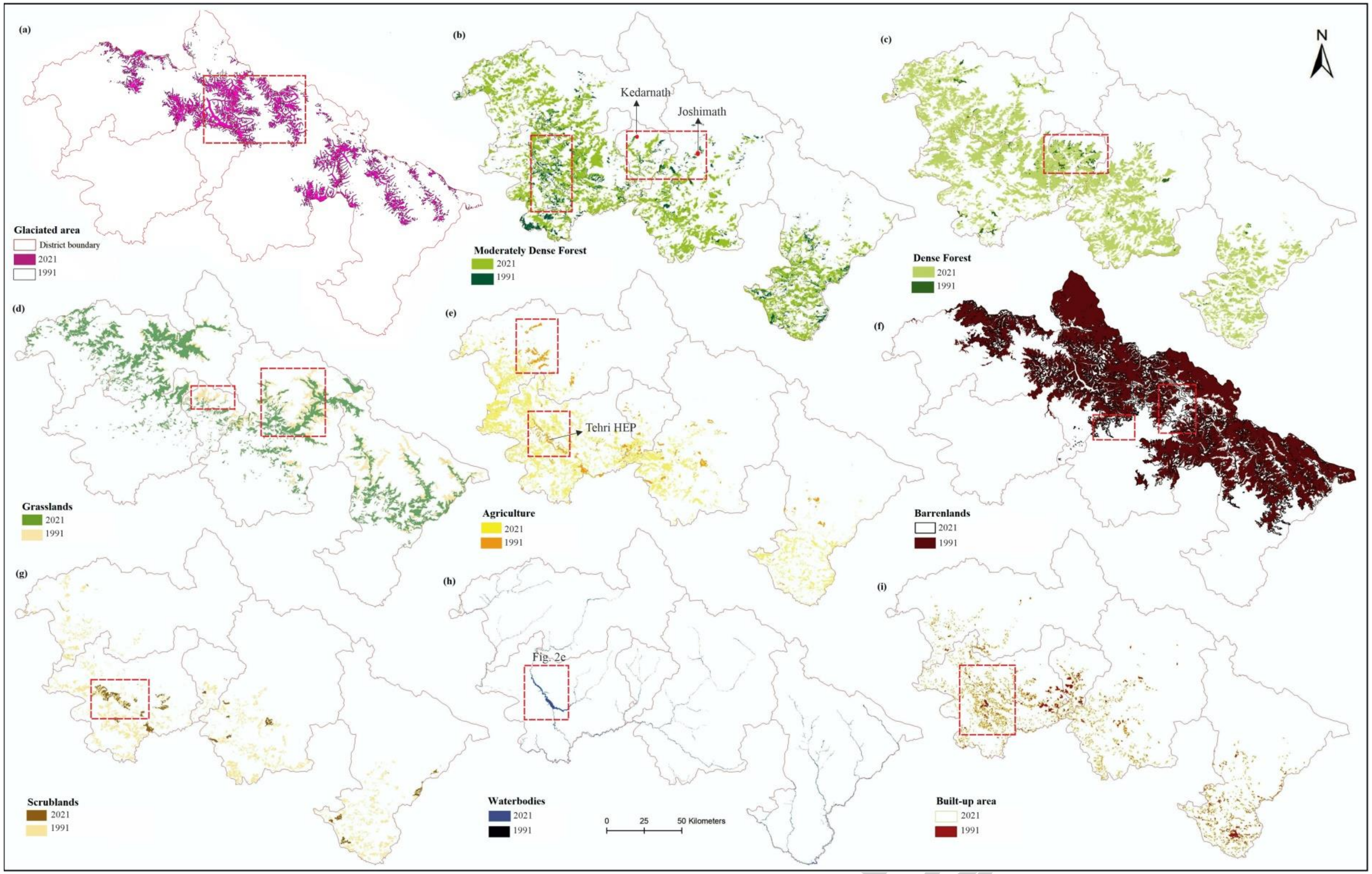

Fig. 3: Spatio-temporal variation of different LU/LC layers. (a) Glaciated. (b) Moderately Dense Forest; (c) Dense Forest; (d) Grasslands; (e) Agriculture; (f) Barren land; (g) Scrubland (Shrubland); (h) Waterbody; (i) Built-up/settlement. Red quadrangular highlights relatively more change in each layer during the years 1991-2020.

The moderately dense forest area decreased from 4316±347 km^2 in 1991 to 3856±161 km^2 in 2020. Such a 10.6 % (~460±56 km^2) decrease mostly occurred during the years 2001-2011 (Fig. 2c-d). This decrease is relatively more prominent in the SW part of the study area, i.e., around Tehri HEP (Hydroelectric power plant), commissioned in year 2006, and the Kedarnath-Joshimath region (Fig. 3b). Such decreasing pattern is attributed to tourist influx, population rise, associated job opportunities, and subsequent increased demand of built-up area in Kedarnath-Joshimath region (Fig. 4f-h) and Tehri HEP (Fig. 5a-b). Rana et al. (2007); Hoffman et al. (2019) have also noted such anthropogenic influence around Tehri HEP. Such a decrease in the forest cover, along with frequent forest fires, not only alters the carbon sink budget in the region but also affects local climate (Liu et al., 2019; Marifatul et al., 2022).

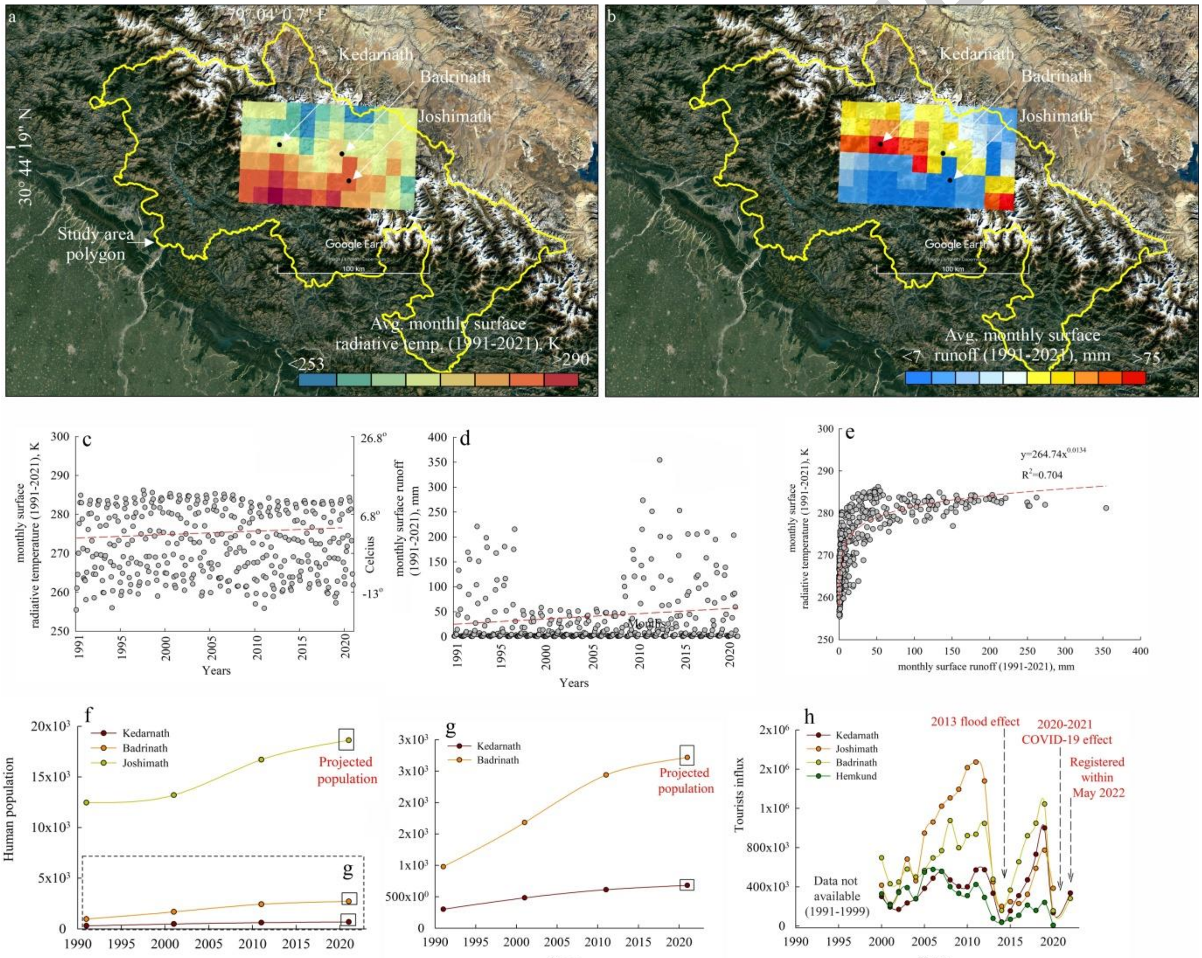

Fig. 4: Climatic and anthropogenic influence in Kedarnath-Joshimath region. (a) Average monthly surface radiative temperature (1991-2021); (b) Average monthly surface runoff (1991-2021); (c-d) Temporal variation in monthly surface radiative temperature and monthly surface runoff. Data source: FLDAS_NOAH01_C_GL_M model (McNally et al. 2018). Spatial resolution of dataset: 0.1° (~10 km); (e) Power-law correlation of surface radiative temp. and surface runoff in this region; (f) Human population data of Kedarnath, Badrinath, and Joshimath. Data Source: Census 1991, 2001, 2011 (https://censusindia.gov.in/ data retrieved on 14/01/2022); (h) Tourists influx in Kedarnath, Joshimath, Badrinath, and Hemkund. Data source: https://uttarakhandtourism.gov.in/, data retrieved on 01/05/2022.

Like the moderately dense forest, dense forest area also decreased from 6418±516 km^2 in 1991 to 6073±255 km^2 in 2020. Such a 5.3 % (~345±42 km^2) decrease mostly occurred during the years 2011-2020 (Fig. 2c-d). This decrease is also relatively more prominent around the Kedarnath region (Fig. 3c), which is attributed to the rising population, tourist influx, and subsequent demand for road/infrastructure (Fig. 4f-h). This observation of forest area decrease can be further validated from similar findings in recent studies that noted ~1000-1400 km^2 decrease in forest area in Uttarakhand during the years 1990-2009 (Chakraborty et al., 2017; India state of Forest report, 2019). The forests being the main source of timber, fuel wood and cultivable land, the deforestation rates have accelerated globally in recent years, particularly in relatively more populated Asian countries (Brandt et al., 2017 and the references within). However, in Uttarakhand, the continuous shrinking of the forest area has been attributed to infrastructure development and escalating ecological crisis (Farooqui and Maikhuri 2007). Further, the ~23 % increase in forest scrub (shrub) from 498±40 km^2 in the year 1991 to 616±25 km^2 in the year 2020 (Fig. 2c-d) can be attributed to frequent forest fires and climate change-induced biological changes in flora species (Saxena and Singh, 1982; Kumar and Ram, 2005; Ropars and Boudreau, 2012). Apart from glacial areas and forests, grassland also witnessed a decrease, which is elaborated below.

The grasslands indicated a decrease from 3479±280 km^2 in year 1991 to 3332±139 km^2 in year 2020. This ~4% (147±18 km^2) decrease mostly occurred during the years 2011-2020 (Fig. 2c-d). Relatively higher decrease in the grasslands occurred around Kedarnath-Joshimath region (Fig. 3d). Though the NE region, upstream Kali valley also witnessed grassland decrease, we have emphasized relatively more vulnerable regions. The increase in surface radiative temperature, population increase, and tourist influx in this region during the years 1991-2021 (Fig. 4) are attributed as main reasons of grassland decrease. Various studies have noted the decrease in grasslands owing to climate change and resultant temperature increase because higher temperature induces a shift in plant species towards higher altitudes, resulting in reduced species richness and altered species composition and resultant less productivity (Schirpke et al. 2017 and reference within). Pandey et al. (2021) have related deterioration of grasslands in Uttarakhand to anthropogenic interferences for development activities and tourism facilities, which can be validated from our observation of population increase and tourist influx (Fig. 4f-h).

The agricultural land decreased from 1810±145 km^2 in 1991 to 1720±72 km^2 in 2020. This ~4.9% (90±11 km^2) decrease mostly occurred during the years 2001-2011 (Fig. 2c-d). This decrease is relatively more prominent in the SW and western part of the study area i.e., around Tehri HEP (Hydroelectric power plant) and upper Tons valley, respectively (Fig. 3e). This decrease around the Tehri HEP is attributed to the waterbody (reservoir) of the HEP that has taken over part of the agricultural land. Further, tourist influx, population rise (Fig. 5a-b), and subsequent increased demand for the built-up area have contributed to the decrease in agricultural land. Joshi (2018) has related the abandonment of agricultural land with the rural-out migration from the region. Unlike the compound effect of Tehri HEP in the SW part, the decrease in agricultural land in the western part, i.e., upper Tons valley may be attributed to rural-out migration affecting the vegetation productivity (Maikhuri et al. 2001; Shukla et al. 2018). Bisht et al. (2018) have related this practice of rural-out migration with the shortage of indigenous food resources and nutritional scarcity in Uttarakhand (NW Himalaya).

Following the decreasing LU/LC layers, the layers that attained increase are as follows. Barren land (6.8%), scrubland (or shrubland) (12.2%), waterbodies (66.6%), and built-up area (49.4%) (Fig.2c-d).The barren land increased from 8550±688 km^2 in 1991 to 9137±383 km^2 in 2020. This ~6.8% (587±71 km^2) mostly occurred during the years 1991-2001 followed by the years 2011-2020. This increase is relatively more prominent in the upper catchment of Alaknanda valley (Fig. 3f). Since this increase approximately coincides with the grassland decrease (Fig. 3d), it might be attributed to the increase in surface temperature and population pressure in the region from 1991 to 2021 (Fig. 4). Temporally increasing surface temperature induces a shift in plant species towards higher altitudes, resulting in reduced species richness and altered species composition and less productivity (Schirpke et al. 2017 and reference within). Such increased surface temperature has been observed to affect the soil moisture retention capacity and alter the nutrient export, finally leading to barren land (Bai et al. 2019). Other mountain chains have also noted an increase in barren land owing to changing climate, overgrazing, and increased built-up due to population pressure (Wu et al., 2010; Huang et al., 2020). Notably, barren land might increase further in view of an increasing trend of surface temperature and anthropogenic pressure in the region (Banerjee et al., 2021; Chakraborty and Ghosal, 2022).

The shrubland increased from 1080±86 km^2 in the year 1991 to 1212±50 km^2 in year 2020. This ~12.2% (132±16 km^2) increase mostly occurred during the years 2011-2020 (Fig. 2c-d). This increase is relatively more prominent in the SW part of the study area, i.e., around Tehri HEP (Hydroelectric power plant) (Fig. 3g). This increase in the shrubland spatially coincides with the decreasing moderately dense forest in this region. Notably, the decrease in the moderately dense forest in this region is attributed to population rise, tourist influx and associated various job opportunities leading to increased demand of built-up area (Fig. 5a-b).

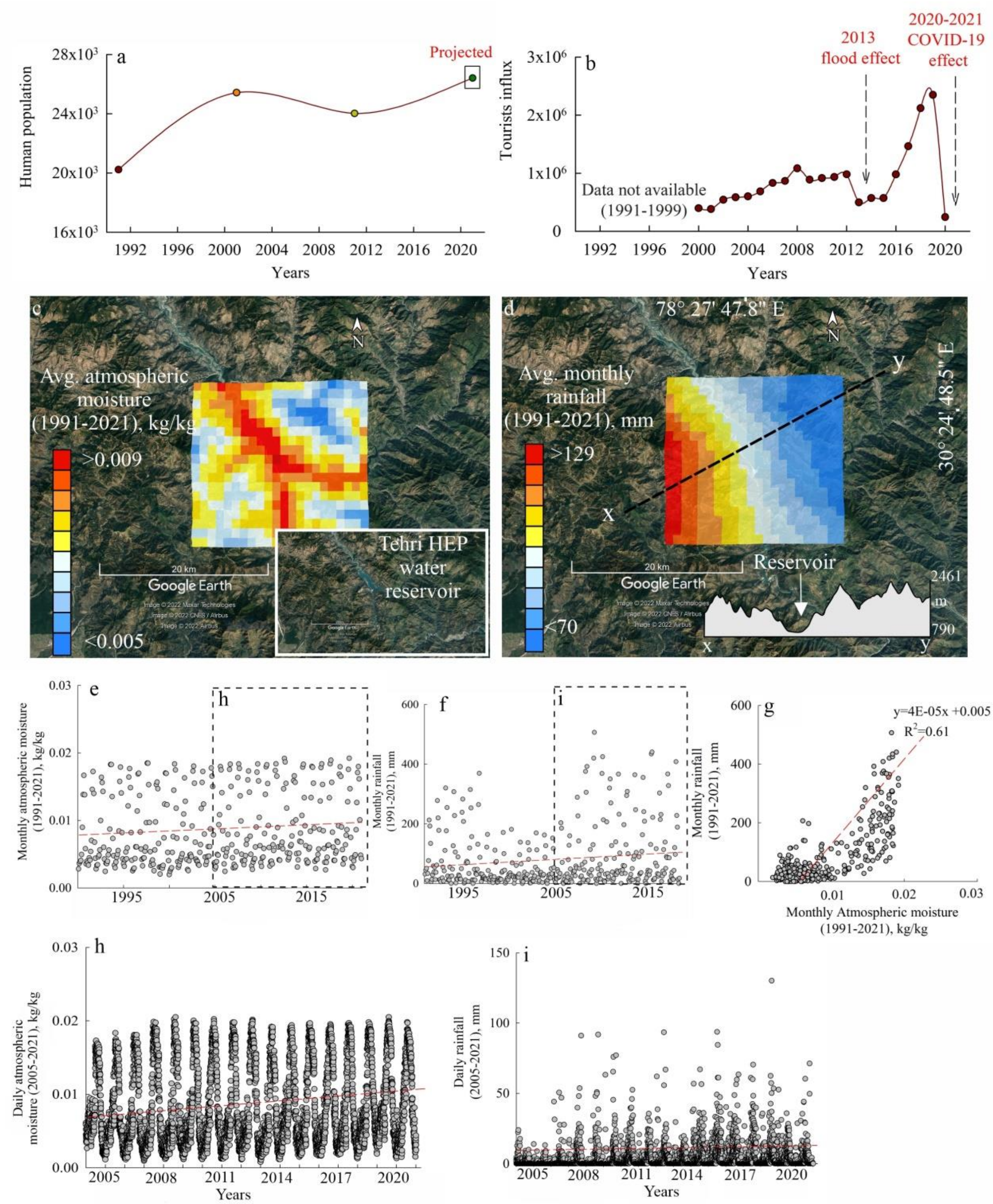

Fig. 5: Climatic and anthropogenic influence in and around Tehri (a) Human population data of Tehri. Data Source: Census 1991, 2001, 2011 (https://censusindia.gov.in/ data retrieved on 14/01/2022). Note that the population data of year 2021 is projected based on 11.5% population growth rate (Source: https://main.mohfw.gov.in/, data retrieved on 01/05/2022); (b) Tourists influx in Tehri. Data source: https://uttarakhandtourism.gov.in/, data retrieved on 01/05/2022; (c) Average monthly atmospheric moisture (1991-2021); (d) Average monthly rainfall (1991-2021); (e, f, h, i) Temporal variation in atmospheric moisture and rainfall. Monthly climatic data source: FLDAS_NOAH01_C_GL_M model (McNally et al. 2018). Spatial resolution of dataset: 0.1° (~10 km). Source of daily datasets: FLDAS_NOAH001_G_CA_D model (Jacob et al. 2021); (g) Linear correlation of rainfall and atmospheric moisture in this region.

The waterbody area has increased from 129±10 km^2 in the year 1991 to 215±9 km^2 in the year 2020. This ~66.6% (86±11 km^2) increase mostly occurred during the years 2001-2011, which is mainly attributed to the reservoir of the Tehri HEP, commissioned in year 2006 (Fig. 2c, d, e). Notably, the creation of the Tehri HEP and its waterbody have decreased moderately dense forest and agriculture, whereas increased shrubland and the built-up area directly and/or indirectly. Apart from the Tehri HEP waterbody, Srinagar HEP (commenced in year 2014-2015) waterbody, Maneri HEP waterbody (commenced before year 1991) also constitute waterbody in the study area. Rautela et al. (2002); Rana et al. (2007) have also observed various socioeconomic implications, including agricultural and forest land decrease due to such hydropower waterbody of Tehri HEP. Such decrease, particularly in forest areas, might be related to decreased shear strength of hillslope material around the Tehri water reservoir, which is mainly responsible for enhanced mass movements in this region (Kumar and Anbalagan, 2019).

The existence of this waterbody (~52 km^2) not only altered land use/land cover and socio-economic conditions but also affected the local climate. It is noted to have higher concentration of atmospheric moisture that possibly contributes to the higher rainfall in the nearby region (Fig. 5c-i). Unlike atmospheric moisture, which is concentrated over the waterbody, rainfall is mostly concentrated in the SW side of the reservoir that may be due to topography controlled wind direction (x-y section in Fig. 5d). Further, the atmospheric moisture and rainfall have also increased temporally, particularly after year 2005-2006 (commencement of water reservoir). Notably, the atmospheric moisture and rainfall in the region show linear correlation (R^2=0.6) and imply a sudden increase in rainfall at a threshold atmospheric moisture (0.015 kg/kg). Such pattern of reservoir induced atmospheric moisture richness has been related to the enhanced evaporation from the reservoirs (Zhu et al. 2022).

The built-up area has increased from 425±34 km^2 in 1991 to 635±26 km^2 in 2020. This ~49.4% (210±25 km^2) increase mostly occurred during the years 1991-2001 followed by the years 2011-2020 (Fig. 2c, d). This increase is relatively more prominent in the in the SW part of the study area i.e., around Tehri HEP (Hydroelectric power plant) (Fig. 3i), as discussed above. The rising human population, tourist influx, and migration of rural population towards such semi-urban centres are the main reasons for this region's increased built-up. Notably, the growth in the tourism industry in the Indian Himalaya, particularly western Himalaya (Uttarakhand, Himachal Pradesh, and Jammu-Kashmir) recorded approximately a four-fold increase (about 270%) in tourist influx between 2001–2019 (Chakraborty and Ghosal, 2022).

We are of understanding that the possible uncertainty of different spatial resolutions of Landsat and LISS-IV imagery (details in Supplementary Table 1), used in the study, can be minimized/eliminated if same land use/land cover features are mapped in both images with least uncertainty i.e., 4.1% (Supplementary Fig. 2). Here, 4.1% uncertainty refers to the difference (%) in the measured distances/area in the Landsat and LISS-IV imagery. In view of the unavailability of LISS-IV (spatial resolution of 5.8m) imagery for years 1991, 2001, and 2011, Landsat imagery was used. Further, though we have validated the area of different land use/land cover layers, particularly glacial and forests with the published datasets (Roy et al., 2016; Forest Survey of India, 2017; RGI Consortium, 2017), possibility of minor areal difference cannot be ignored. Such differences might exist owing to following factors (i) relative changes in the LU/LC feature between the time periods of imagery of published dataset and our mapping (ii) spatial resolution dependent mapping errors.

5.0 CONCLUSION

Our study has observed two hotspots having relatively more changes in the land use/land cover layers. The first hotspot belongs to the Kedarnath-Joshimath region, whereas the second belongs to the Tehri HEP waterbody region that hosts the tallest (260.5 m) hydropower dam in India. The Kedarnath-Joshimath region is noted to experience a relatively more decrease of grasslands, dense forests, and glaciers, primarily attributed to the relatively high surface radiative temperature from 1991 to 2021, growing population, tourism, and subsequent infrastructure development. Such land use/land cover changes have been observed to affect the soil moisture retention capacity and alter the nutrient export, finally leading to the barren land. The barren land in this region might increase further in view of the increasing trend of surface temperature and anthropogenic factors (tourist influx/population increase). The second hotspot, i.e., the Tehri HEP waterbody region, is witnessing decreasing agricultural land and moderately dense forest, whereas increase in built-up and shrubland. The decrease in agricultural land is attributed to the existence of the waterbodies that submerged part of the agricultural land and the abandonment of the remaining agricultural land for better economic prospects like tourism and subsequent demand for the more built-up area. Further, the regional tourism industry's growth recorded approximately a four-fold increase (about 270%) between year 2001 and 2019.

The present study attempted to evaluate the land use/land cover changes in Uttarakhand, NW Himalaya (India) during 1991-2020 and observed changing climatic conditions and anthropogenic factors (population/tourism pressure) as possible causes of such changes. Notably, the two extreme climatic-geomorphic events (landslides/flood) within last 10 years killing more than 6000 people originated in and around the first hotspot i.e., Kedarnath-Joshimath region. Such spatial co-existence of recent disaster events and relatively higher land use/land cover changes imply the possibility of more such events in the region. In view of the growing influence of changing climate and anthropogenic pressure, the concept will be explored further in future prospects to quantify the potential risks of such disasters.

Author contribution: VK, YP, DSB, and NR conceived the idea. SA and SK compiled the datasets and performed satellite imagery analysis. NC, SK, and FK analysed required climatic and population/tourism data. All authors contributed to the writing of the final draft.

Competing interests: The authors declare that they have no conflict of interest.

Dataset availability: Monthly and daily climatic datasets are openly accessible at https://giovanni.gsfc.nasa.gov/giovanni/ (NASA, 2021). The tourist influx and population datasets are available at https://uttarakhandtourism.gov.in/ and https://censusindia.gov.in/ , respectively.

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REFERENCES

Bai, Y., Ochuodho, T. O., & Yang, J. (2019). Impact of land use and climate change on water-related ecosystem services in Kentucky, USA. Ecological Indicators, 102, 51-64.

Banerjee, A., Dimri, A. P., & Kumar, K. (2021). Temperature over the Himalayan foothill state of Uttarakhand: Present and future. Journal of Earth System Science, 130(1), 1-14.

Benn, D. I., & Owen, L. A. (1998). The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: review and speculative discussion. Journal of the Geological Society, 155(2), 353-363.

Bhambri, R., Bolch, T., Chaujar, R. K., & Kulshreshtha, S. C. (2011). Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. Journal of Glaciology, 57(203), 543-556.

Bisht, I. S., Mehta, P. S., Negi, K. S., Verma, S. K., Tyagi, R. K., & Garkoti, S. C. (2018). Farmers' rights, local food systems, and sustainable household dietary diversification: A case of Uttarakhand Himalaya in north-western India. Agroecology and sustainable food systems, 42(1), 77-113.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state and fate of himalayan glaciers. Science, 336(6079), 310–314.

Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., & Zhang, Y. (2019). Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region. The Hindu Kush Himalaya Assessment, 209–255.

Brandt, J. S., Allendorf, T., Radeloff, V., & Brooks, J. (2017). Effects of national forest-management regimes on unprotected forests of the Himalaya. Conservation Biology, 31(6), 1271–1282.

Caballero, C. B., Ruhoff, A., & Biggs, T. (2022). Land use and land cover changes and their impacts on surface-atmosphere interactions in Brazil: A systematic review. Science of The Total Environment, 808, 152134.

Chakraborty, A., Ghosh, A., Sachdeva, K., & Joshi, P. K. (2017). Characterizing fragmentation trends of the Himalayan forests in the Kumaon region of Uttarakhand, India. Ecological Informatics, 38, 95–109.

Chakraborty, P., & Ghosal, S. (2022). Status of mountain-tourism and research in the Indian Himalayan Region: a systematic review. Asia-Pacific Journal of Regional Science, 1-35.

Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T., & Sikka, D. R. (2015). Western disturbances: a review. Reviews of Geophysics, 53(2), 225-246.

Dirmeyer, P. A., Niyogi, D., de Noblet-Ducoudré, N., Dickinson, R. E., & Snyder, P. K. (2010). Impacts of land use change on climate. Int. J. Climatol, 30(13), 1905-1907.

Dobhal, D. P., Gergan, J. T., & Thayyen, R. J. (2004). Recession and morphogeometrical changes of Dokriani glacier (1962–1995) Garhwal Himalaya, India. CURRENT SCIENCE-BANGALORE-, 86(5), 692–696.

Fang, Z., Ding, T., Chen, J., Xue, S., Zhou, Q., Wang, Y., ... & Yang, S. (2022). Impacts of land use/land cover changes on ecosystem services in ecologically fragile regions. Science of The Total Environment, 831, 154967.

Farooquee, Nehal & Maikhuri, Rakesh. (2007). Role of the State on Forests: Case of Uttarakhand. Economic and Political Weekly. 42. 3537-3540.

Forest Survey of India Report (2017). Ministry of Environment & Forests, Government of India, New Delhi. https://fsi.nic.in/forest-report-2017, data retrieved on 05/05/2022.

Gupta, S., Anand, S., & Gwal, S. (2018). Inbound tourism in Uttarakhand, India, before and after the 2013 Kedarnath disaster–evidence derived from social networking sites using GIS. Current Science, 1755-1759.

Gupta, V., Jamir, I., Kumar, V., & Devi, M. (2017). Geomechanical characterization of slopes for assessing rockfall hazards in the Upper Yamuna Valley, Northwest Higher Himalaya, India. Himalayan Geology, 38(2), 156-170.

Hoffmann, E. M., Konerding, V., Nautiyal, S., & Buerkert, A. (2019). Is the push-pull paradigm useful to explain rural-urban migration? A case study in Uttarakhand, India. PloS one, 14(4), e0214511.

Houze Jr, R. A., McMurdie, L. A., Rasmussen, K. L., Kumar, A., & Chaplin, M. M. (2017). Multiscale aspects of the storm producing the June 2013 flooding in Uttarakhand, India. Monthly Weather Review, 145(11), 4447-4466.

Huang, J., Zhang, G., Zhang, Y., Guan, X., Wei, Y., & Guo, R. (2020). Global desertification vulnerability to climate change and human activities. Land Degradation & Development, 31(11), 1380-1391.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. v., Mayewski, P. A., … Baillie, J. E. M.

(2020). Importance and vulnerability of the world’s water towers. Nature, 577(7790), 364–369.

IPCC-2013, Stocker, T. (Ed.). (2014). Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge university press.

Jacob, J., Slinski, K. (2021). FLDAS Noah Land Surface Model L4 Central Asia Daily 0.01 x 0.01 degree, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: [20/03/2022], 10.5067/VQ4CD3Y9YC0R

Jamir, I., Gupta, V., Thong, G. T., & Kumar, V. (2020). Litho-tectonic and precipitation implications on landslides, Yamuna valley, NW Himalaya. Physical Geography, 41(4), 365-388.

Kulkarni, A. V., & Karyakarte, Y. (2014). Observed changes in Himalayan glaciers. Current Science, 106, 237–244.

Kumar, A., & Ram, J. (2005). Anthropogenic disturbances and plant biodiversity in forests of Uttaranchal, central Himalaya. Biodiversity & Conservation, 14(2), 309-331.

Kumar, R., & Anbalagan, R. (2019). Landslide susceptibility mapping of the Tehri reservoir rim area using the weights of evidence method. Journal of Earth System Science, 128(6), 1-18.

Kumar, V., Jamir, I., Gupta, V., & Bhasin, R. K. (2021). Inferring potential landslide damming using slope stability, geomorphic constraints, and run-out analysis: a case study from the NW Himalaya. Earth Surface Dynamics, 9(2), 351-377.

Li, D., Tian, P., Luo, H., Hu, T., Dong, B., Cui, Y., ... & Luo, Y. (2020). Impacts of land use and land cover changes on regional climate in the Lhasa River basin, Tibetan Plateau. Science of The Total Environment, 742, 140570.

Liu, Z., Ballantyne, A. P., & Cooper, L. A. (2019). Biophysical feedback of global forest fires on surface temperature. Nature communications, 10(1), 1-9.

Maikhuri, R. K., Rao, K. S., & Semwal, R. L. (2001). Changing scenario of Himalayan agroecosystems: loss of agrobiodiversity, an indicator of environmental change in Central Himalaya, India. Environmentalist, 21(1), 23-39.

Marifatul Haq, S., Calixto, E. S., Rashid, I., Hussain Malik, A., Kumar, M., & Ahmad Khuroo, A. (2022). Anthropogenic pressure and tree carbon loss in the temperate forests of Kashmir Himalaya. Botany Letters, 1-13.

Martha, T. R., Roy, P., Govindharaj, K. B., Kumar, K. V., Diwakar, P. G., & Dadhwal, V. K. (2015). Landslides triggered by the June 2013 extreme rainfall event in parts of Uttarakhand state, India. Landslides, 12(1), 135-146.

McNally A. (2018). FLDAS Noah Land Surface Model L4 Global Monthly 0:1 × 0:1 degree (MERRA-2 and CHIRPS), Goddard Earth Sciences Data and Information Services Center (GES DISC), Greenbelt, MD, USA, https://doi.org/10.5067/5NHC22T9375G.

Mukherjee, P. K., Jain, A. K., Singhal, S., Singha, N. B., Singh, S., Kumud, K., ... & Patel, R. C. (2019). U-Pb zircon ages and Sm-Nd isotopic characteristics of the Lesser and Great Himalayan sequences, Uttarakhand Himalaya, and their regional tectonic implications. Gondwana Research, 75, 282-297.

Nainwal, H. C., Negi, B.D.S., Chaudhary, M., Sajwan, K. S. and Gaurav, A. (2008). Temporal changes in rate of recession: Evidences from Satopanth and Bhagirath Kharak glaciers, Uttarakhand, using Total Station Survey; Current Science 94(5) 653–660.

Pandey, A., Singh, G., Palni, S. et al. Application of remote sensing in alpine grasslands cover mapping of western Himalaya, Uttarakhand, India. Environmental Monitoring and Assessment 193, 166 (2021).

Paudel, B., Zhang, Y. L., Li, S. C., Liu, L. S., Wu, X., & Khanal, N. R. (2016). Review of studies on land use and land cover change in Nepal. Journal of Mountain Science, 13(4), 643-660.

Raina, V. K., & Srivastava, D. (2008). Glacier atlas of India. Geological Society of India. 315pp. 13:978-8-185-86780-9.

Rana, N., Sati, S. P., Sundriyal, Y. P., Doval, M. M., & Juyal, N. (2007). Socioeconomic and environmental implications of the hydroelectric projects in Uttarakhand Himalaya, India. Journal of Mountain Science, 4(4), 344-353.

Rana, N., Singh, S., Sundriyal, Y. P., & Juyal, N. (2013). Recent and past floods in the Alaknanda valley: causes and consequences. Current Science, 105(9), 1209-1212.

Rana, N., Sundriyal, Y., Sharma, S., Khan, F., Kaushik, S., Chand, P., ... & Juyal, N. (2021). Hydrological Characteristics of 7th February 2021 Rishi Ganga Flood: Implication towards Understanding Flood Hazards in Higher Himalaya. Journal of the Geological Society of India, 97(8), 827-835.

Rautela, P., Rakshit, R., Jha, V. K., Gupta R. K., and Munshi, S., (2002). GIS and remote sensing-based study of the reservoir-induced land-use/land-cover changes in the catchment of Tehri dam in Garhwal Himalaya, Uttaranchal (India). Current science, vol. 83, no. 3

Rawat, J. S., & Kumar, M. (2015). Monitoring land use/cover change using remote sensing and GIS techniques: A case study of Hawalbagh block, district Almora, Uttarakhand, India. The Egyptian Journal of Remote Sensing and Space Science, 18(1), 77–84.

Rawat, P. K., Tiwari, P. C., & Pant, C. C. (2012). Climate change accelerating land use dynamic and its environmental and socioeconomic risks in the Himalayas: Mitigation through sustainable land use. International Journal of Climate Change Strategies and Management, 4(4), 452–471.

Reid, R. S., Kruska, R. L., Muthui, N., Taye, A., Wotton, S., Wilson, C. J., & Mulatu, W. (2000). Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of southwestern Ethiopia. Landscape Ecology, 15(4), 339-355.

RGI Consortium. (2017). Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Centre. Data retrieved on 05/05/2022. DOI: https://doi.org/10.7265/4m1f-gd79.

Ropars, P., & Boudreau, S. (2012). Shrub expansion at the forest–tundra ecotone: spatial heterogeneity linked to local topography. Environmental Research Letters, 7(1), 015501.

Roy, P.S., P. Meiyappan, P.K. Joshi, M.P. Kale, V.K. Srivastav, S.K. Srivasatava, M.D. Behera, A. Roy, Y. Sharma, R.M. Ramachandran, P. Bhavani, A.K. Jain, and Y.V.N. Krishnamurthy. (2016). Decadal Land Use and Land Cover Classifications across India, 1985, 1995, 2005. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1336

Saxena, A. K., Pandey, P., & Singh, J. S. (1982). Biological Spectrum and other structural functional attributes of the vegetation of Kumaun Himalaya. Vegetatio, 49(2), 111-119.

Scherler, D., Bookhagen, B., & Strecker, M. R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature Geoscience 2011 4:3, 4(3), 156–159.

Schirpke, U., Kohler, M., Leitinger, G., Fontana, V., Tasser, E., & Tappeiner, U. (2017). Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their resilience. Ecosystem Services, 26, 79-94.

Shekhar, M. S., Devi, U., Paul, S., Singh, G. P., & Singh, A. (2017). Analysis of trends in extreme precipitation events over Western Himalaya Region: intensity and duration wise study. J. Indian Geophys. Union, 21(3), 225-231.

Shukla, R., Sachdeva, K., & Joshi, P. K. (2018). Demystifying vulnerability assessment of agriculture communities in the Himalayas: a systematic review. Natural Hazards, 91(1), 409-429.

Singh, P., Arora, M., & Goel, N. K. (2006). Effect of climate change on runoff of a glacierized Himalayan basin. Hydrological Processes: An International Journal, 20(9), 1979-1992.

Singh, R. B., & Mal, S. (2014). Trends and variability of monsoon and other rainfall seasons in Western Himalaya, India. Atmospheric Science Letters, 15(3), 218-226.

Singh, R. B., & Mal, S. (2014). Trends and variability of monsoon and other rainfall seasons in Western Himalaya, India. Atmospheric Science Letters, 15(3), 218-226.

Sohl, T. L., & Sohl, L. B. (2012). Land-use change in the atlantic coastal pine barrens ecoregion. Geographical Review, 102(2), 180–201.

Sun, J., & Mahrt, L. (1995). Determination of surface fluxes from the surface radiative temperature. Journal of the atmospheric sciences, 52(8), 1096-1106.

Taloor, A. K., Kumar, V., Singh, V. K., Singh, A. K., Kale, R. v., Sharma, R., Khajuria, V., Raina, G., Kouser, B., & Chowdhary, N. H. (2020). Land Use Land Cover Dynamics Using Remote Sensing and GIS Techniques in Western Doon Valley, Uttarakhand, India. 37–51.

Tiwari, P. C. (2000). Land-use changes in Himalaya and their impact on the plains ecosystem: need for sustainable land use. Land Use Policy, 17(2), 101–111.

Valdiya, K.S. (1980) Geology of the Kumaun Lesser Himalaya: Dehra Dun, India. Wadia Institute of Himalayan Geology, 291p.

Vannay, J. C., & Grasemann, B. (2001). Himalayan inverted metamorphism and syn-convergence extension as a consequence of a general shear extrusion. Geological Magazine, 138(3), 253-276.

Verma, A., Schmidt-Vogt, D., de Alban, J. D. T., Lim, C. L., & Webb, E. L. (2021). Drivers and mechanisms of forest change in the Himalayas. Global Environmental Change, 68, 102244.

Wu, Z., Zhang, H., Krause, C. M., & Cobb, N. S. (2010). Climate change and human activities: a case study in Xinjiang, China. Climatic Change, 99(3), 457-472.

Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y. U. N., & Wilkes, A. (2009). The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. Conservation Biology, 23(3), 520-530.

Zhu, G., Sun, Z., Xu, Y., Liu, Y., Zhang, Z., Sang, L., and Wang, L. 2022. Evaporation loss estimation of the river-lake continuum of arid inland river: Evidence from stable isotopes, Hydrol. Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/hess-2022-75, in review.

LIST OF FIGURES AND TABLES

Fig. 1: Location map of the study area. Inset highlights the position of study area in the NW Himalaya. Elevation data source: ALOS PALSAR RTC © JAXA/METI, accessed through ASF DAAC, https://asf.alaska.edu, retrieved on 02/03/2022, DOI: 10.5067/Z97HFCNKR6VA. Location of extreme climatic-geomorphic events in the region; 20 July 1970, 16 June 2013, and 7 Feb. 2021 are also shown.

Fig. 2: Spatio-temporal variations in land use/land cover (LU/LC). (a) year 1991 LU/LC; (b) year 2020 LU/LC; (c) Area wise distribution of different LU/LC layers in year 1991, 2001, 2011, and

2020; (d) Relative increase (%) of different LU/LC layers in different decades; (e) Tehri HEP (Hydroelectric power) water reservoir.

Fig. 3: Spatio-temporal variation of different LU/LC layers. (a) Glaciated. (b) Moderately Dense Forest; (c) Dense Forest; (d) Grasslands; (e) Agriculture; (f) Barren land; (g) Scrubland (Shrubland); (h) Waterbody; (i) Built-up/settlement. Red quadrangular highlights relatively more change in each layer during the years 1991-2020.

Fig. 4: Climatic and anthropogenic influence in Kedarnath-Joshimath region. (a) Average monthly surface radiative temperature (1991-2021); (b) Average monthly surface runoff (1991-2021); (c-d) Temporal variation in monthly surface radiative temperature and monthly surface runoff. Data source: FLDAS_NOAH01_C_GL_M model (McNally et al. 2018). Spatial resolution of dataset: 0.1° (~10 km); (e) Power-law correlation of surface radiative temp. and surface runoff in this region; (f) Human population data of Kedarnath, Badrinath, and Joshimath. Data Source: Census 1991, 2001, 2011 (https://censusindia.gov.in/ data retrieved on 14/01/2022); (h) Tourists influx in Kedarnath, Joshimath, Badrinath, and Hemkund. Data source: https://uttarakhandtourism.gov.in/, data retrieved on 01/05/2022.

Fig. 5: Climatic and anthropogenic influence in and around Tehri (a) Human population data of Tehri. Data Source: Census 1991, 2001, 2011 (https://censusindia.gov.in/ data retrieved on 14/01/2022). Note that the population data of year 2021 is projected based on 11.5% population growth rate (Source: https://main.mohfw.gov.in/, data retrieved on 01/05/2022); (b) Tourists influx in Tehri. Data source: https://uttarakhandtourism.gov.in/, data retrieved on 01/05/2022; (c) Average monthly atmospheric moisture (1991-2021); (d) Average monthly rainfall (1991-2021); (e, f, h, i) Temporal variation in atmospheric moisture and rainfall. Data source: FLDAS_NOAH01_C_GL_M model (McNally et al. 2018). Spatial resolution of dataset: 0.1° (~10 km); (g) Linear correlation of rainfall and atmospheric moisture in this region.

Supplementary Fig. 1: Spatio-temporal variation in land use/land cover. (a) Year 2001 ; (b) Year 2011.

Supplementary Fig. 2: Mapping comparison of LISS-IV (year 2020) and Landsat 8 (year 2020) imagery**.** Google earth satellite image highlights the position of regions that are taken to compare mapping in both imageries. Image A, C, E, G belong to LISS-IV imagery, whereas B, D, F, and H belong to Landsat 8 imagery, respectively. A-B (Dense Forest), C-D (Built-up/settlement), E-F (Forest scrub), G-H (Barren land).

Supplementary Table 1: Source of satellite imagery used in the study.