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Research article

Application of remote sensing and GIS in environmental monitoring in the Hindu Kush Himalayan region

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Abstract: The Hindu Kush Himalaya (HKH) region encompasses the largest mountain system in the world extending from Myanmar in the East to Afghanistan in the West and covering the whole or part of Bangladesh, Bhutan, China, India, Nepal, and Pakistan. The region plays a vital role in providing ecosystem services and is the basis of the livelihoods of over 200 million people. The water and other ecosystem services provided by the HKH forms lifeline for one third of humanity. In the past few decades, human activities and global warming have contributed to environmental degradation in significant portion of the region. Decreasing glacier area, growth in glacial lake size, unprecedented rainfall, changes in land use and land cover, forest degradation, floods and glacial lake outburst floods (GLOFs), landslides, and shortfalls in agricultural crop production are among the many problems brought on by such change. These issues need timely monitoring and supervision if they are to lead to a better understanding of the state of the environment, and the scale of the damages that has already been done. Effective monitoring of the environment, and an improved understanding of the same requires valuable information and data that can be extracted through the application of geospatial technologies such as remote sensing (RS) and geographic information system (GIS). This paper provides an overview of such research conducted in the HKH region. It shows how change assessment has been undertaken in thematic areas such as glacier, glacial lake, land use, land cover, and disaster events like floods, landslides and droughts and how sets of data collected over specific intervals of time are being used to identify and monitor the condition of the environment from the past to the present, and in the long run. Complete database sets and analyses pertaining to these areas are made available online to facilitate access to information. Data formulation and further research are necessary to reduce scientific uncertainty and understand the impacts induced by climate change in the HKH. Scientific analyse made during each individual study can be used by decision makers and planners in environmental protection planning and development.

Keywords: Environmental monitoring; mapping; remote sensing; GIS

1. Introduction

The Hindu Kush Himalayan (HKH) region functions as a complex interaction of atmospheric, cryospheric, hydrological, geological and environmental processes that holds special significance for the earth's biodiversity, ecosystem, climate and water cycles [1] The region has high environmental significance: it is home to four global biodiversity hotspots, 488 protected areas (Pas), 330 important bird areas (IBAs), 29 Ramsar sites, and 60 ecoregions. The region itself forms an ecological buffer separating the Tibetan Plateau from South Asia, and influences global climate regulation. The past few decades have seen high levels of environmental changes taking place. Climate change presents numerous problems, and providing ecosystem services, and livelihood options for a growing population is a challenge. Environmental changes may change the roles and functions of ecosystems services for the region's people. Changes in the regional climate are affecting the availability of fresh water, which in turn leads to vulnerabilities in seasonal water availability, biodiversity, ecosystems and agriculture. Past studies have stated that the melting of glaciers is a clear indicator of climate change [2,3] and that change in glacier mass is a visible indicator of rising air temperature. Changes in temperature cause imbalances in the environment and can bring disastrous consequences such as floods, GLOFs, avalanches, landslides, agricultural droughts, hydrological droughts and water shortfalls. We need to take a dramatic step in the monitoring processes and generate comprehensive, transparent, and accurate information in taking crucial and timely action in response to growing concerns regarding the environment. However, monitoring processes based on ground measurement across the HKH region are very difficult and bound by time constraints. Monitoring became possible and easier with the advent of geospatial science and remote sensing technology. The technology makes in understanding past and present situations and figuring out possible changes over the long-term basis. The use of unmanned aerial vehicles (UAVs) to generate high resolution digital elevation models (DEMs) is one of the latest innovations in remote sensing technology. DEM differencing has been used to estimate highly accurate data for glacier thickness and volume in the HKH region [4]. Use of such technologies, coupled with field verification to a certain extent, should be prioritize to obtain greater accuracy. Anthropogenic activities across the HKH region have modified our environment at unprecedented rates and scales. Remote sensing has helped generate basic data to undertake an inventory of these changes, and it provides spatial and temporal information for further monitoring. GIS, on the other hand, analyses spatial information and integrate it in the decision making process. It aggregates data from various inputs and presents them as maps to strengthen general awareness of environmental conditions [5]. ICIMOD as a regional resource centre for geo information and earth observation applications has been focusing on a broad range of issues related to environmental change. They include the melting of glacier and snow, alternations in land use and land cover, disasters like floods, landslides, GLOFs, and drought. We have been conducting long-term research on these thematic areas so as to understand the processes of environmental change and its impacts on them. Such research aims to enhance knowledge on the subject and generate scientific data, findings and information. The results obtained from these areas provide beneficial datasets to scientists, policymakers and development planners to address and make decision on many levels.

Hence, the purpose of this paper is to present the findings produced by those thematic focus areas in the HKH region, taking advantage of geospatial science and remote sensing techniques. The data and information generated will be used to understand the environmental conditions and analyses of the decadal changes will further add to our knowledge of environmental change in the HKH region. This will be helpful in long-term monitoring processes.

2. Study area

The HKH region covers 4.2 million square kilometer of the mountainous regions of the Hindu Kush, Karakoram and Himalayan mountain ranges. These mountainous regions are the source of ten major rivers systems (Figure 1), including the Indus, Ganges, Brahmaputra, Amu Darya, Irrawaddy, Salween, Mekong, Yangtse, Yellow River and Tarim [6,7]. The region is characterized by extremes of altitude, relief and climate [8]. The HKH region has the greatest ice coverage of about 60,000 square kilometers outside the polar caps [7]. It is rich in biodiversity, forests, rangelands, landscapes, nature and cultural values. Agriculture is the main occupation for over 70% of the population [9]. Climatically, the HKH region is immensely influenced by three circulation systems: the Indian summer monsoon, western disturbances and the East Asian monsoon. The region has a strong temperature difference with a mean annual temperature below 0 °C in the higher mountains usually above 4000 m asl and greater than 20 °C in the lower plains [10].

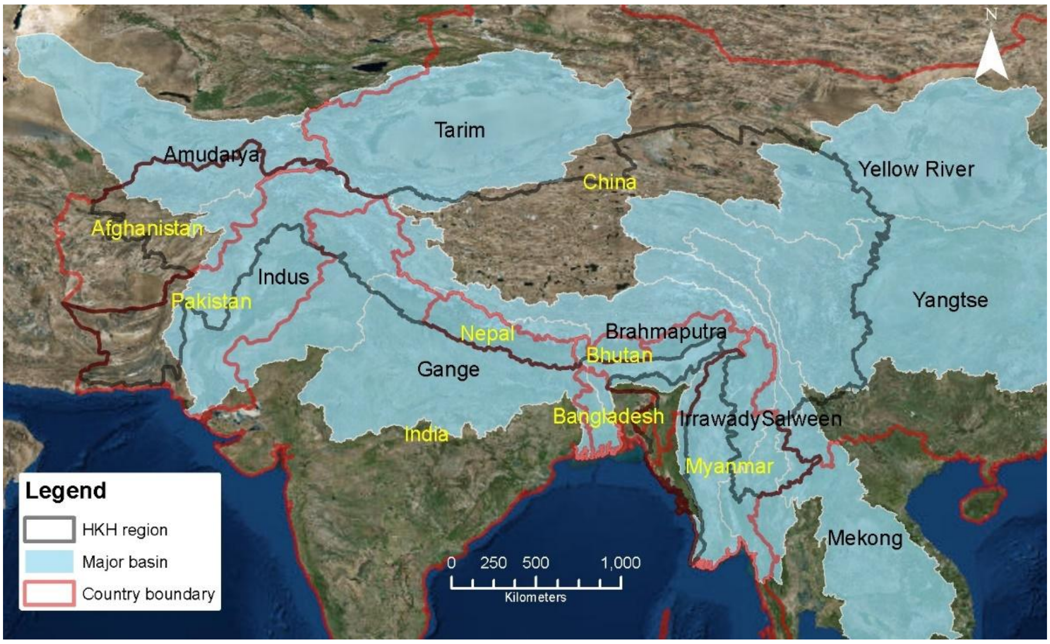


Figure 1. Ten major basins of the HKH region.

3. Materials and methods

This study employs the use of geospatial science and remote sensing techniques to study and monitor certain thematic areas in the HKH region (Table 1). A variety of spatial and temporal data pertaining to glaciers, glacial lakes, snow, land use and land cover (LULC), forest fragmentation, floods, landslides and agricultural drought were generated, and all these data were applied in understanding past and ongoing changes in the environment. Remote sensing data mostly derived from Landsat satellites has been widely applied in glaciers, glacial lakes, LULC and forest fragmentation monitoring due to their higher spatial resolution, extended spectral range and greater temporal coverage. The satellite data covering the study area were acquired from the Global Land Cover Facility (GLCF) (http://glcfapp.glcf.umd.edu:8080/esdi/) and earth explorer (http://earthexplorer.usgs.gov/). The Landsat MSS/TM/ETM+/Landsat OLI 1T images have helped not only monitor changes, but also provide valuable information regarding the impacts of such changes with reference to global climate. Remote sensing software such as eCognition Developer and ERDAS Imagine were used to generate data for glaciers and glacial lakes. The methodology applied was semi-automatic, using object-based image classification in eCognition Developer software for glaciers [7] and using NDWI for glacial lakes [11]. ERDAS Imagine was used for image mosaicking and other image processing. Satellite images such as Landsat TM/ETM+ were used to map glaciers of the HKH region in 2011, whereas Landsat MSS/TM/ETM+ were used to generate variation in glacier data for Bhutan and Nepal between the 1980s, 1990, 2000 and 2010 [12,13], and for Myanmar between 1977, 1990, 2000, 2009. Landsat MSS/TM/ETM+/Landsat OLI 1T were used for mapping glacial lakes in the Koshi basin in Nepal (1977, 1990, 2000, 2010), Bhutan (1990, 2000, 2010, 2014) and Myanmar (1977, 1990, 2000, 2009) in order to produce precise findings and gain a better understanding of the nature of change as it has taken place over a thirty-year period. Snow cover monitoring is taking place within daily and/or weekly time frames using MODIS-Terra and Aqua snow products at a 500 m spatial resolution. Total maximum snow cover extent has been monitored by eight day composite products from Terra and Aqua sensors that overpass every morning and afternoon, with additional improvements achieved by removing cloud cover using combination and spatio-temporal filters. An object-based image analysis approach was applied for mapping land use and land cover (LULC) to obtain homogenous image objects using eCognition Developer software applying multi resolution segmentation techniques [14]. A land cover classification system (LCCS) was applied to group the classes according to the main land cover type. In Nepal, the mapping and monitoring of LULC was inspected for 1990 and 2009 using higher resolution spatial images from the Landsat Thematic Mapper (1990/1992) and the Linear Imaging Self-Scanning Sensor (LISS III), 2009 [14]. Gains and losses in land use/cover were examined using Land Change Modeler (LCM) in IDRISI Taiga software from Clark Labs [15]. The ArcGIS Landscape Fragmentation Tool was applied to study and monitor forest fragmentation and edge effects [14,16]. This tool mapped forest fragmentation based on forest and non-forest land cover. For flood and landslide monitoring, the International Charter for Space and Major Disaster (ICS) and Sentinel Asia provided high resolution satellite images for free to allow the mapping and monitoring of disaster areas. eCognition Developer software, ERDAS Imagine and Arc GIS are generally used in the rapid response mapping of affected areas. For agriculture monitoring, the Normalized Difference Vegetation Index (NDVI) acquired by the moderate resolution sensor MODIS satellite at 16-day intervals and a 250 m spatial resolution was used to analyse and prepare maps to predict increases or shortfalls in production.

Table 1. Details of images, methodologies and software used for different studies.

Study	Satellite used	Acquisition date	Methodology	Softwares
Glaciers	Landsat MSS/TM/ETM+	1977, 1982, 1990, 2000, 2001, 2002, 2004, 2005, 2006, 2007, 2008, 2009, 2010	Semi-automatic using object based image classification	eCognition Developer, Erdas Imagine, Arc GIS
Glacial lakes	Landsat MSS/TM/ETM+ /Landsat OLI 1T	1977, 1990, 2000, 2004, 2005, 2006, 2007, 2009, 2010, 2014, 2015	Semi-automatic using NDWI and manual mapping	Erdas Imagine, Arc GIS
Snow	MODIS-Aqua/Terra	2000−2015	MODIS eight-day snow product with additional improvements achieved by removing cloud cover using a combination and spatio-temporal filters	MODIS
Land use and land cover	Landsat MSS/TM/ETM+	1990, 2000, 2010	Semi-automatic using object based image classification, land cover classification system (LCCS)	eCognition Developer, IDRISI Taiga, Arc GIS Landscape Fragmentation Tool
Floods and landslides	Landsat, GeoEye, ALOS, Sentinel, Worldview	2008, 2010, 2013, 2015	Semi-automatic using object-based image classification and manual mapping	eCognition Developer, Arc GIS
Agricultural droughts	MODIS-Aqua/Terra	2001−2010	A total of 230 NDVI 16-day composite images	MODIS

4. Results

This section will discuss some key thematic areas that are under long-term observation and monitoring in order to get findings that support understanding of the condition of the environment in the HKH region.

4.1. Glacier monitoring

There were a number of past studies conducted on monitoring glacier numbers and the condition of glacial areas and their changing patterns; but these were mostly based on field measurements and topographic maps. In 1999/2000, satellite images from different sources were used in the mapping and monitoring of glaciers in different regions. In 2011, glaciers across the entire HKH region were mapped and monitored using Landsat TM/ETM+ images from 2005 ± 3 years to understand the spatial variation of glaciers by applying remote sensing and GIS technology. The study identified a total of 54,000 individual glaciers with an overall area of 60,000 km^2. The total glaciated area of the HKH region was found to be 1.4%. Large variations of glaciated areas were found in each basin, but the greatest proportion of glaciers was observed in the Indus basin (3.8% of the total basin area), and then the Ganges (3.7%) and the Brahmaputra (3.2%) basins. Further, a detailed study and observation of the decadal variability of glaciers for the 1980s, 1990, 2000 and 2010 was carried out for Nepal, Bhutan and Myanmar at a regional scale, and the Jhelum and Shyok basins from the Indus, Khumbu and Langtang basins of Nepal at a local scale, using Landsat MSS/TM/ETM+ images from the 1980s up to 2010. The decadal study from Nepal showed that the total area decreased by 24% between the 1980s and 2010. The number of glaciers increased by 11% as a result of fragmentation and shrinking. The glaciers receded on average by 38 km^2 per year. The rate of loss of glacial area between the 1980s–1990 was almost twice what it was between 1990–2000 and 2000–2010. Few examples of glacial change in the Nepal Himalayas are shown in Figure 2. Over the course of the 30 years, the glaciers Rikha Samba, Mera, and Kimjung showed decrements in total glaciated area by 1.2 km^2, 0.5 km^2, and 1.1 km^2 respectively.

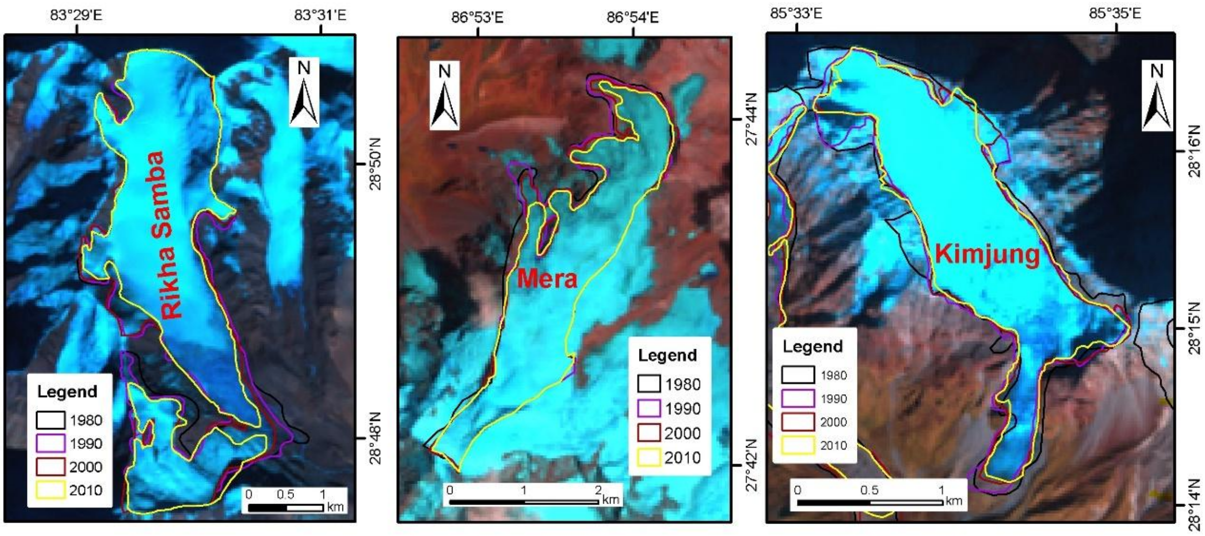


Figure 2. Monitoring of different glaciers from 1980 to 2010 using Landsat images in the Nepal Himalayas.

Similarly, glaciers studied for 30 years in Bhutan show that about 23% of glacial area was lost between 1980s and 2010 with the highest loss 11.6% between 1980s and 1990, and the lowest 6.7% between 2000 and 2010. The trend of glacier area change from the 1980s to 2010 was −6.4%. In the Myanmar Himalayas, the loss of glaciers was 18% between 1977 and 2009. At a local scale, the glaciers in Jhelum and Shyok basins showed that the melting rate was higher from 1990 to 2000 than it was from the 1980s to 1990, and 2000 to 2010. Similarly, the total glacial area decreased by 26% in Langtang valley and 27% in Khumbu valley over the 30-year period, and experienced an average rate of loss of 1.49 km^2/year and 0.57 km^2/year respectively. Further, 21 years of climatic data were used to understand the implications of rising air temperatures on glaciers over the Langtang and Khumbu valleys. It showed that both the basins were warming at a very high rate compared to the annual mean temperature of Nepal. Glacier areas in Langtang and Khumbu are decreasing in response to rises in decadal mean temperatures as well as rises in annual mean temperature rates (Figure 3). The areas of smaller glaciers at lower elevations have reduced more rapidly than the areas of bigger glaciers. Loss of glacier at each 100 m elevation was also observed as they largely determine how sensitive glaciers are to changes in temperature. Based on DEM differencing, the monitoring of spatial patterns of elevation changes over individual glaciers using the geodetic method (Rikha Samba glacier in Nepal and Thana glacier in Bhutan) is ongoing. Besides this, a UAV was deployed before and after the melt and monsoon seasons to monitor and understand the mass loss and surface velocity of Lirung glacier with high spatial accuracy in Langtang basin, Nepal. The result showed that the spatial variability of melt rates is very high and that mass losses of ice cliffs are higher than the average [4]. UAV has also been deployed to study other glaciers in Nepal and later in other part of the HKH region to monitor and understand the mass, thickness and volume loss of glacier. This helps to identify the availability of water resources, assess past and present situations of the environment and aid future climate predictions.

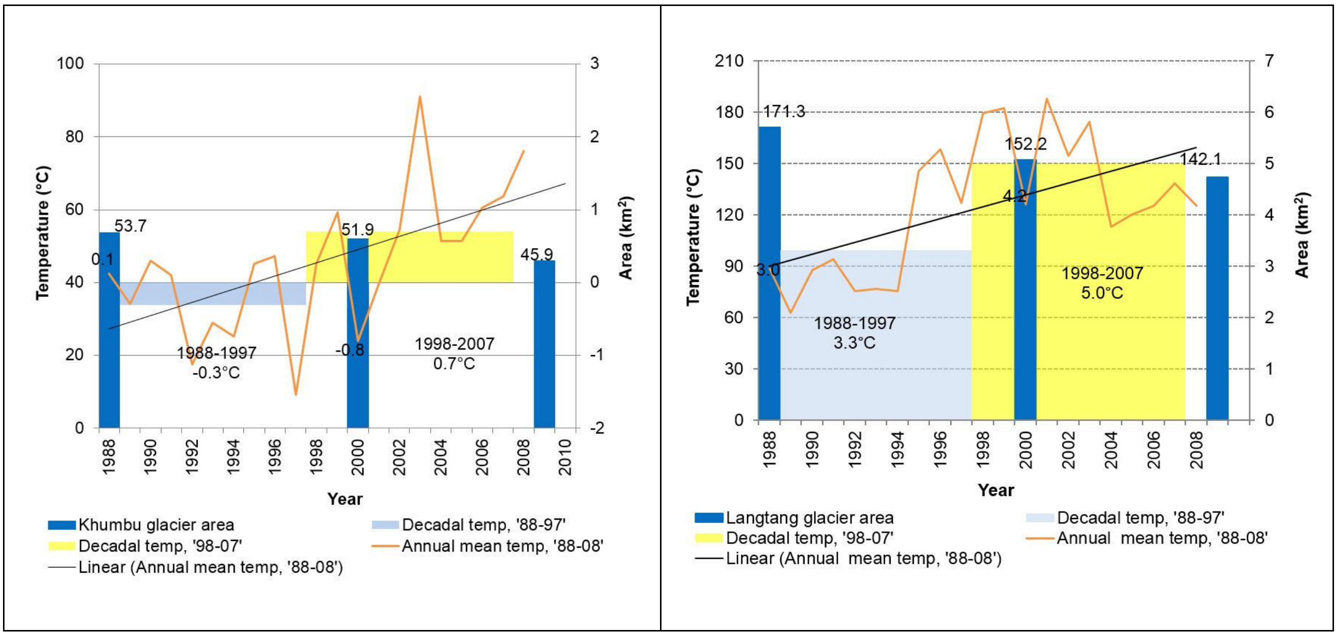
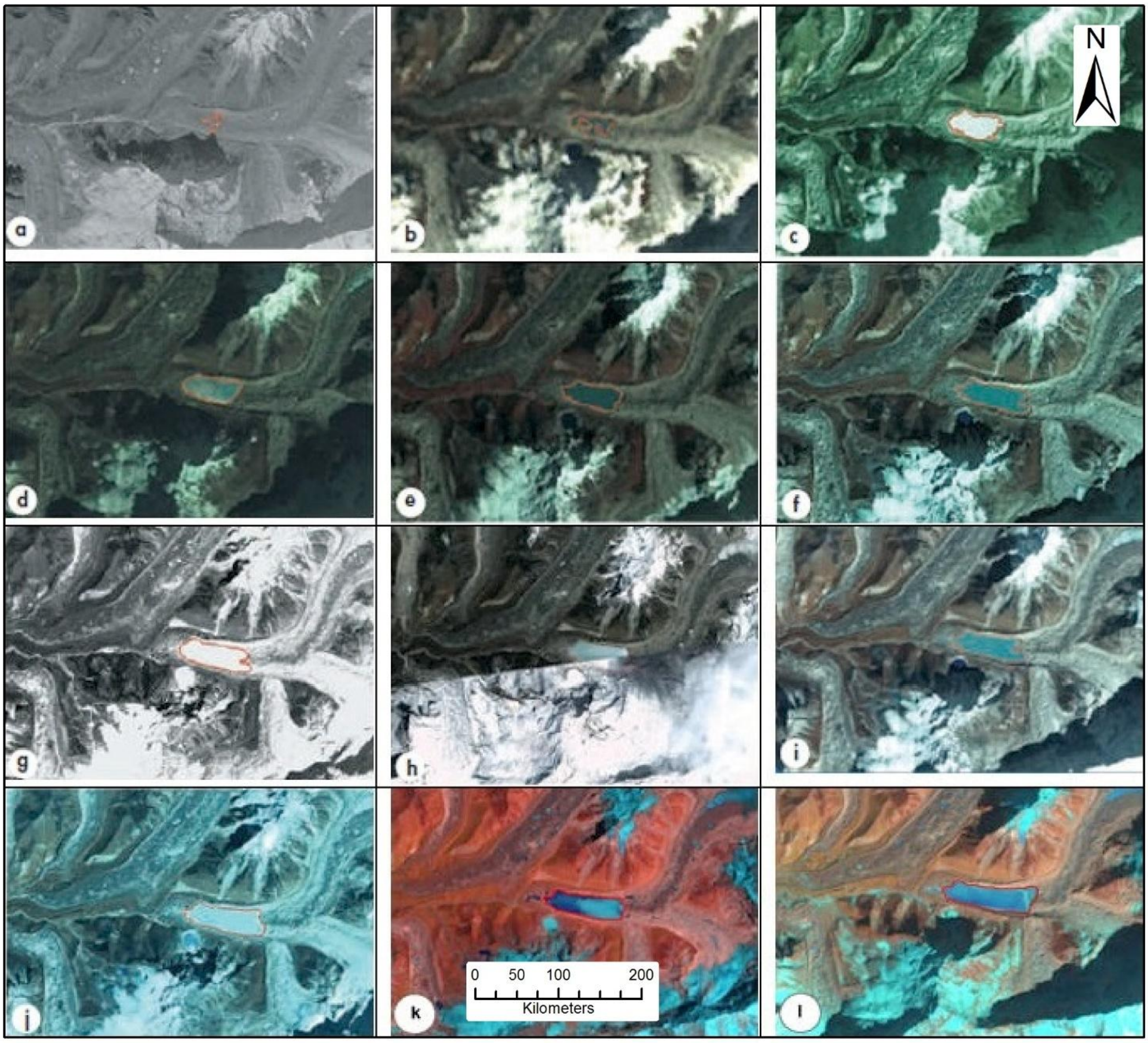


Figure 3. Relationship of glaciers with average decadal and annual mean temperature in Khumbu and Langtang valley [13].

4.2. Glacial lake monitoring

The systematic and comprehensive study and monitoring of glacial lakes started in Nepal in 1999/2000, based mainly on topographic maps published between 1960 and 1982 [17], and in Bhutan in 2001, based on topographical survey maps published between the 1950s to 1970s by the Survey of India [18]. In 2009/2010 a new glacial lake inventory for Nepal was produced, based on Landsat images taken in 2005 and 2006 by applying remote sensing and GIS techniques. A comparison of these two studies showed notable changes in the areas of many glacial lakes. Glacial lakes are related to water related natural hazards and need to be monitored regularly to assess their potential hazards. Nepal, Bhutan, China and other part of the HKH region have experienced a number of GLOFs in the past decades [19-23,17,18,24]. In 2010, a study found that 21 glacial lakes in Nepal are potentially critical. Among them, three lakes—Tsho Rolpa, Imja Tsho (Figure 4) and Thulagi have been categorized as highly prioritized for continuous monitoring and observation. These lakes are under long-term observation through remote sensing techniques. Observations of these lakes were mostly based on Landsat images since they are free of cost. An analysis of images of the Imja Tsho lake (Figure 4) shows that the lake's area had increased by 0.8 km^2 from 1977 to 2015. From 1977 to 1990, the lake showed a rapid increase in area by 0.23 km^2. Over the five-year period (2010–2015), the increase in lake area was almost similar to the increase that had taken place in the lake area over the ten-year period (2000–2010). From 2000 to 2010, the lake increased by 0.202 km^2, while from 2010 to 2015, the lake increased by 0.206 km^2. The data show that the lake's area has increased abruptly over the most recent five-year period. The monitoring of the HKH region and its inventory preparation are being under taken using Landsat images. Glacial lakes in Bhutan have been monitored from 1990 to 2014, and Myanmar from 1977 to 2009, using Landsat MSS/TM/ETM+/Landsat OLI 1T images. The study in Bhutan showed that the number of glacial lakes has decreased by 7.18%. i.e., from 2228 in 1990 to 2068 in 2014, but glacial area has increased by 1.12% from 99.659 km^2 in 1990 to 100.78 km^2 in 2014. However, in Myanmar, glacial lake number and area have increased by 37.6% and 17.8% respectively over the 32-year period.



Source: a) Corona (15 Dec, 1962); b) Landsat MSS (15 Oct 1975); c) Space shuttle (2 Dec 1983); d)Landsat 5TM (11 Dec 1989); e) Landsat 5 TM (22 Sep 1992); f) Landsat 7 ETM+ (30 Oct 2000); g) LISS 3 (19 March 2001); h) Google Earth (Feb 2003); i) Landsat 5 TM (5 Nov 2005); j) ALOS AVHNIR-II (11 Mar 2009); k) Landsat 7 ETM+ (25 April 2010); l) Landsat 8 OLI 1T (10 Feb 2015)

Figure 4. Monitoring of the Imja Tsho in Nepal, a critical glacial lake, on the basis of a series of satellite images collected from 1962 to 2015.

4.3. Snow cover monitoring

Monitoring of snow cover trends and characteristics is crucial for understanding regional climate change and managing water resources. Figure 5 shows the seasonal variation in snow cover in 10 major river basins of the HKH region from 2000 to 2015 using MODIS. Snow cover varies largely in all basins over space and time. The highest average snow cover was found in the Qinghai basin (42%) which was double the snow cover area of the entire HKH region. The Brahmaputra and Indus basins also tend to have higher snow cover areas than the other remaining basins. These basins are highly influenced by westerlies so the accumulation of snow is higher during winter. Basins like Irrawaddy and Mekong have lower snow cover contributions, less than 5% each. The snow cover area across 10 major river basins was 8.4% of the total area of the HKH region. Trend analyses show no major positive or negative trends in snow cover area in all the major river basins of the HKH region.

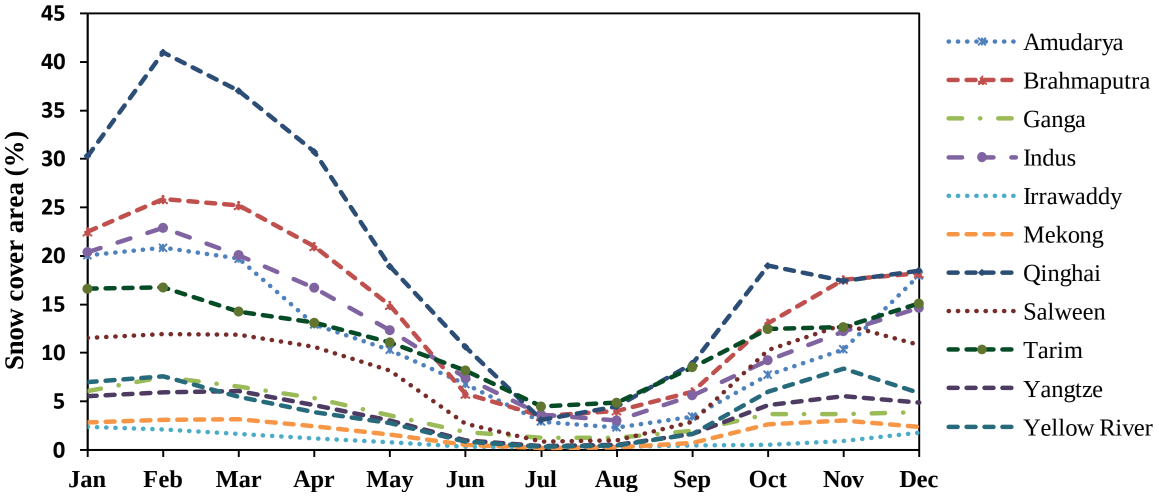


Figure 5. Monitoring of average seasonal snow cover from 2000 to 2015 using MODIS in 10 major river basins of the HKH region.

4.4. Land use and land cover (LULC) monitoring

Land use and land cover (LULC) change is one of the most important and easily detectable indicators of change in ecosystem services and livelihood support systems. In the HKH region, the mapping of LULC has made a consistent monitoring of land use/land cover patterns possible. The task has been made an easier by the advent of high spatial resolution satellite images, advanced image processing and GIS technologies. In Nepal, the mapping and monitoring of LULC was inspected for the years 1990, 2000, and 2010, and a case study covering two decades—1990 and 2009 was done for Nepal's Kailash Sacred Landscape (KSL). The study showed that forests are the dominant form of land cover in Nepal. In 1990 and 2010, forests covered areas of 59,181 km^2 and 57,538 km^2, with contributions of 40.21% and 39.09% respectively to the total geographical area of the country. The decrease in total forest area over the course of 20 years was about 1.12%. A 1.31% increase was observed in cropland from 1990 to 2010, while grass-land increased by 0.28% during the same period. In KSL, forests occupied 24.4% of the total landscape area in 1990; this decreased to 22% in 2009. Major changes were observed: from forest to cropland and forest to grassland, from grassland to cropland and from snow/glacier to barren land. Predictions for 2030 indicated further loss of forest cover (by 4%), and cropland (by 5%); however, a slight increase in grassland has been predicted. No observations were made of land being converted into forest. Likewise, a study of the distribution of forest fragmentation showed that remarkable changes took place between 1990 and 2009, and that further change is expected in 2030. In the 19 years, large core forest area decreased by 10% and perforated forest area by 58%, while medium core, small core, edge and patch forest area increased by 6%, 12%, 1.8% and 26.7% respectively.

The mapping and monitoring of land use and land cover change was undertaken for Bhutan, Pakistan and the Greater Chittagong area of Bangladesh (Figure 6) for the years 1990, 2000 and

2010. In Bhutan, forest area increased from 25,558 to 26,732 km^2. i.e., by 1174 km^2 between 1990 and 2010, equivalent to an average annual growth rate of 59 km^2/year (0.22%). This was a result of annual plantation initiatives and better management plans. However, there was an overall reduction in grassland, shrubland, and barren areas. Forest and scrub forest covered almost 75% of the land area of Bhutan. The greatest change from non-forest to forest (277 km^2) was observed in Bumthang and Wangdue Phodrang districts of Bhutan. In Pakistan, the mapping and monitoring of forest cover for the years 1990, 2000, and 2010 revealed significant deforestation. Forest had diminished by 170,684 ha in 20 years at a rate of 0.38% per year. The rate of deforestation was at its highest from 2000 to 2010, where much of the loss took place at the western borders with Afghanistan. An analysis of land cover in the Greater Chittagong district of Bangladesh showed that hill forests were the dominant form of land cover in the Chittagong geographical area. The same analysis showed that, in 1990, the percentage of areas covered by hill forest was 55.66%, by forests was 14.86%, and by shrubland was 14.52%. Similarly, irrigated herbaceous crops covered 3.47% of the area, and rained herbaceous crops 2.11% of the area. Rural areas covered 3.10%, bare soil 2.21%, and lakes and rivers 1.89%, and 1.11% respectively. Crops in sloping land/tea, and urban regions occupied 0.40% of the total area. In 2010, hill forests, shrubland, irrigated herbaceous crops and rained herbaceous crops covered 50.34%, 17.94%, 14.91% and 4.87% of the total area respectively. Figure 6 shows the land cover map of the greater Chittagong district of Bangladesh. Due to continuing shifting cultivation, many patches of forest land have been cleared for vegetation, used for cultivation temporarily, and then abandoned and to revert to their natural state. Mostly, forest land has been converted to permanent agricultural land and orchards; some deforested land has been turned into rubber plantations.

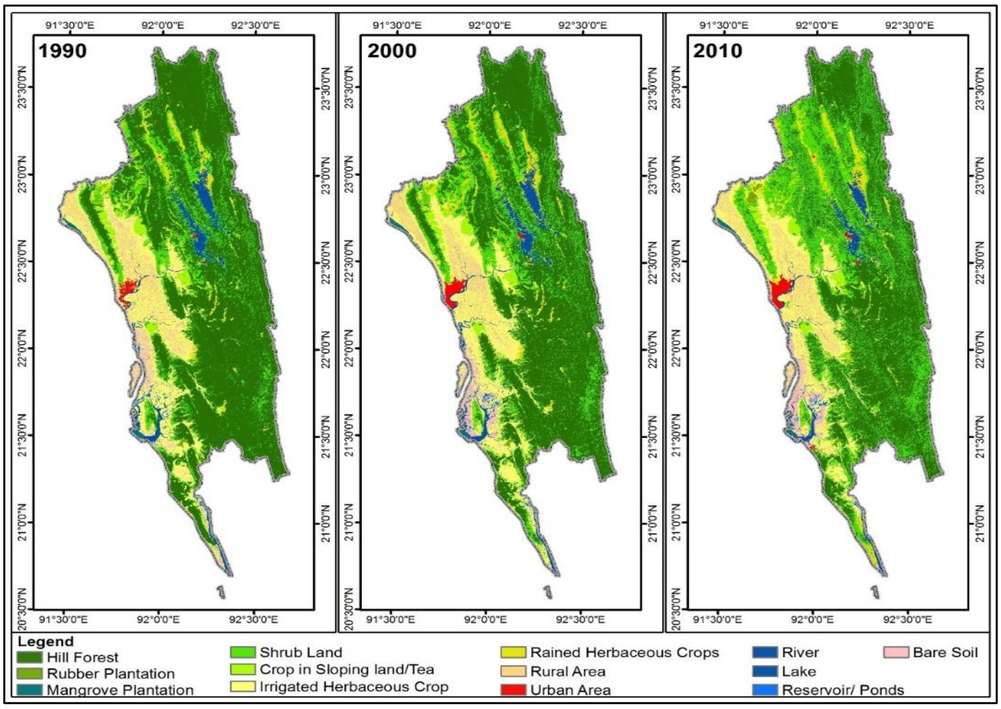


Figure 6. Land cover map of the Greater Chittagong district of Bangladesh for 1990, 2000 and 2010.

4.5. Flood and landslide monitoring

Satellite based monitoring has become an integral part of providing updated information on ongoing disaster events such as floods and landslides in near real time across the HKH region. A monitoring of disaster events and supporting disaster response have been undertaken throughout regional member countries using rapid response mapping. Continuous monitoring and rapid damage assessment of a number of flood events—the 2008 Koshi floods, the 2010 floods in Pakistan, and the 2013 floods in Uttarakhand have been carried out using high resolution pre and post-event satellite images provided by ICS, SA, USGS, NASA, JAXA and ISRO. Support has been provided for the mapping and monitoring of landslide events such as the Jure landslide, the Koshi basin landslide, the Langtang landslide and the more than 2000 landslides triggered by the 25 April 2015 earthquake. Mapped landslide data are being used in preparing landslide susceptible maps for rapid damage assessment by utilizing high resolution satellite images and Google Earth. Space technology and remote sensing techniques have proved to be very practical in helping recognize the scale of devastation and plan strategies related to relief supply and other response interferences.

4.6. Agricultural drought monitoring

Agriculture is an important source of income and sustenance for a majority of the population in the HKH region. The effective and constant monitoring of agricultural production is imperative to predicting increases and shortfalls in production due to climatic variability, rainfall anomalies, etc. An agriculture monitoring system integrating the application of remote sensing, geospatial data and ground based information has been developed to collect comprehensive information on agriculture. This system incorporates past climatic data and crop condition patterns, and compares both with data from the current growing season to provide timely information on possible crop production. Remote sensing data such as the Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), and rainfall are used to generate maps to predict increases or shortfalls in production. Anomalies in crop production can be viewed in graphs or figures at District and Village Development Committee (VDC) levels. In cases where effective impact assessment is necessary, such information is delivered to decision makers on time so that preparedness plans to improve food security and reduce drought issues, among others, may be made.

5. Discussion

Remote sensing is one of the most reliable and promising techniques used to simultaneously analyse and monitor a large area, especially in remote mountain regions. This study presents the uses of remote sensing and GIS in collecting information on different thematic areas and relating that information to efforts towards understanding and monitoring environments in the HKH region. Glaciers are sensitive climate indicators and are subjected to the monitoring of environmental change and climate change. Shrinkages or changes in glaciers provide clear evidence of climate change, and in some cases, disappearances indicate the speed of the present change on a regional and global scale. These changes have implications locally and regionally for water resources, and globally for sea level rise. Glacial retreat often leads to the formation of glacial lakes, or the expansion of existing glacial lakes, which creates potential for GLOF events. The associated increases in regional and local hazards also increase risk for communities. The earliest HKH glacier inventories were compiled for only certain parts of the region using different approaches without any comprehensive coordinated assessment. A long-term consistent glacier inventory of the HKH region was later prepared using a common approach with support from partner institutes in regions like Pakistan and China to support assessments of glacier status. Further studies on decadal changes in glaciers in some regional countries (Bhutan, Nepal, Myanmar, and Pakistan) are being carried out to understand the behaviour of glaciers over time. A long-term monitoring study should be carried out in order to update these data. So, a work with partner institutes in Bhutan, China, Pakistan, and Myanmar has been undertaken to maintain and update this inventory. Decadal changes in glaciers and glacial lakes are being studied to improve the understanding of ongoing changes in glaciers, glacial lakes and glacial hazards. In addition, high resolution satellite images are being acquired, UAVs are being deployed and repeat field expeditions undertaken to generate high resolution DEMs to acquire better results and accuracy regarding glacier thickness and volume. The results will help researchers and scientists understand the impact of climate change on glacial environment. Similarly, for land cover and land use, institutional partners are involved in different stages of developing a common set of legends to be used in the HKH region. They are also involved in mapping land cover types and validating land cover over different periods to provide a complete, consistent and harmonized national land cover map. Remote sensing and GIS have also proven to be effective and practicable tools in disaster management and emergency services. GIS serves to handle the huge amount of datasets necessary for vulnerability, risk and hazard management. It provides tremendous support in disaster preparedness and in implementing rescue operations, evacuation routes, and designing warning systems and centres for emergency operations. An eminent role has been taken up by partner institutes in the HKH region in terms of monitoring and updating information on disaster events. They contribute satellite images, provide the expertise necessary in mapping affected area, and provide damage assessment details to minimize the loss of human life and property through the timely exchange of real time data and information among partner countries. Similarly, remote sensing has been widely used for monitoring drought at national, regional and global scales. It facilitates the monitoring of large geographic areas with frequent and repeated visits to the same area. The data acquired provides timely information that can be used to analyse results by comparing the same with historical data or to predict future changes in terms of increases or shortfalls in production. GIS, on the other hand, helps to produce drought hazard maps for visual analysis as well as to support decision making for drought risk management.

The assessment and monitoring of glaciers, glacial lakes, snow, land use and land cover, and agricultural drought provide an overview of the status of these areas over a wide range, as well as a detailed analysis of individual changes. Increasing trends in glacial retreat, rise in glacial lake area, changes in land cover pattern, recurrence of natural disasters like floods, landslides, GLOFs and drought indicates close links with climate change. One of the main reasons for environmental change is human interference—the clearing of forest areas, and practices like shifting cultivation. Besides, anthropogenic activities such as burning of fossil fuel, agricultural practices, mining, urban activities, application of commercial fertilizers and pesticides, etc. also contribute to the rise in air temperature. Changes in environment and climate are clearly discernible in many parts of the HKH region—glaciers melt or loss in area, exposure of boulders and rocks in glaciers, increase in glacial lake area, unpredicted disasters events, forest fires, unprecedented rainfall and drought. Regular monitoring is necessary to improve knowledge and understanding of environment in the HKH region. Data and information on the areas being studied are updated regularly, shared with relevant persons/institutions for further study and analysis, and the analysed results are presented in the form of maps to strengthen general awareness of the environment among the general public.

The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) shows that the HKH region suffers from a major data gap in terms of any climatic assessment (IPCC 2007). However, studies conducted in different regions represent a significant step forward in terms of bridging the data and information gaps in the HKH region. The complete database and analyses provide basic information for regional level assessments, and the monitoring of different thematic areas supports the development of strategies and policies in relation to climate change. In an effort to assess these regional data around the globe and analyse the changes, a complete database has been made available online in a mountain portal: http://geoportal.icimod.org/. In addition, glacier inventories are also made available in the Global Land Ice Measurements from Space (GLIMS) database [25] and the Randolph Glacier Inventory v:3.0 [26]. Individuals, researchers and scientists are utilizing the available data and information to get a clear picture of environmental change in the HKH region by studying the processes of change, and its potential impacts, scenarios for future water availability, glacial change and hazards, land change patterns, and patterns of global warming. Future scenarios are being projected using global and regional climate models.

The database available online on mountain geoportal facilitates access to information for policy and decision makers, scientists, and the public at large in the region and beyond. This database serves as a pillar in terms of informing policy/decision makers and planners in natural resource management, environmental protection, biodiversity conservation, water resource management, early warning and reporting system and developing sustainable livelihoods, particularly for rural communities in the HKH region.

6. Conclusion

The use of advanced remote sensing and GIS tools and techniques enables researchers to monitor and generate data on different thematic focus areas such as glaciers, glacial lakes, snow, land cover and land use, disasters, and food shortfalls in the HKH region. Findings from these areas help understand and interpret the state of the environment locally as well as regionally. The results show that a number of noticeable impacts related to the environment or to climate change have been observed and documented. Glacial area in most of the regions being studied is decreasing rapidly. The glaciers are shrinking, retreating and fragmenting. Changes in glaciers, approximated over a 30-year period, show that glaciers are retreating at a very fast pace. Smaller glaciers at lower elevations are losing their area more rapidly than bigger glaciers. Glacial retreat rates in Bhutan, Nepal, and Myanmar over the 30-year period have been recorded at 23%, 24% and 18% respectively. Climate change is undoubtedly having an adverse impact on glaciers. Climate change impacts are noticeable in many glacial lakes of the HKH region. The Imja Tsho Lake in Nepal had increased by 0.8 km^2 (from 1977 to 2015). Glacial lakes areas in Bhutan and Myanmar have increased by 1.12% (from 1990 to 2014) and by 17.8% (from 1977 to 2009) respectively. Alternations in land cover form and forest degradation were other indicators of environmental change. The monitoring of land use and land cover for Bhutan, Pakistan and the Greater Chittagong area of Bangladesh for the years 1990, 2000, and 2010 revealed significant decrease in forest area as a result of deforestation and the conversion of forest land into land used for other purposes. Decrease in grassland, shrubland and barren area have also been noted. Frequent occurrence of disasters like floods, landslides, GLOFs and droughts are observed in the HKH region. All these changes appear to be linked primarily with the rise in air temperature, which is mainly caused by human interference and by anthropogenic activities.

An inventory of data related to different thematic areas has served as a baseline, and change analysis will provide further detailed outcomes. The same will be continuously updated in the coming years with support from partner institution in the HKH region with a particular focus on quantifying changes and impacts caused by climate change. The database available online will help foster regional cooperation and promote the sharing and exchange of data at the regional and international levels while ensuring continuous monitoring of the HKH environment. It will also help reduce scientific uncertainty and contribute to the formulation of further research to understand the impacts of climate change. The information provided can inform decision makers as they work to develop environmental programmes and policies in related fields.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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