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Article *in* Journal of the Indian Society of Remote Sensing · May 2019

DOI: 10.1007/s12524-019-01002-9(

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RESEARCH ARTICLE

Mapping Glacial Geomorphology and Livelihood Resources in Urgos Watershed, Lahul and Spiti District, Himachal Pradesh, India

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Received: 24 January 2019 / Accepted: 8 May 2019

Abstract

The Urgos watershed is situated in the rain shadow zone of the Pir Panjal Range of the Lahul Himalaya, where western disturbances dominate with solid precipitation. Consequently ice, permafrost and snow meltwater is the main source of the Urgos Nala (stream), which supports agriculture and replenishes drinking water sources downstream in the watersheds. The effect of small amount of glacier retreat and changes in seasonal snow cover is critical for the functioning of meltwater and high natural resources dependent mountain communities. Agriculture, vegetation, fodder and pasture land in the watershed are all entirely dependent on meltwater. Therefore, the study aims to make a quantitative and large-scale map of the study area in relation to rural livelihood. Resource mapping (1:5000) and quantitative characterization of Urgos watershed are achieved using high-resolution satellite images, digital elevation models, Total Station mapping, differential Global Positioning System and collection of field evidences. The landform evolution in the watershed is a result of intense glaciofluvial processes in the past as well as present. The geomorphic features mapped in the area reveal multiple glacial advances in the watershed, in the past. This has direct links with climatic fluctuations and its impact on agriculture and allied activities for the sustenance of people. The analysis shows 22.49% area under glacier and only 1.04% area of the entire watershed under agriculture, fodder, pasture and vegetation land. This 1.04% area of the watershed plays a significant role in the livelihood of the people.

Keywords Glacier and periglacial geomorphology · Total Station · Resources mapping · Rural livelihoods

Introduction

The main purpose of geomorphological mapping is to understand the processes whereby the surface is changed over time and space. A large-scale geomorphic mapping (1:5000) represents a complete scenario of the landscape and landforms evolution in an area (Gustavsson et al. 2006). In the Himalayan region, mapping of glacio-geomorphological landscapes is crucial for evaluating the past glacier, extent and control on topographic evolution (Rashid et al. 2017). The glacial geomorphology encompasses the impacts of glaciation upon floral and faunal evolution, modification and distribution and includes a study of those areas peripheral to glaciated terrains where drainage pattern alteration, climate, vegetation and soil conditions are all severely affected. In the Himalayan region, several studies have tried to estimate the role of geomorphic processes on glacier changes such as debris

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cover (Collier et al. 2015; Dobhal et al. 2013; Nainwal et al. 2008; Sharma et al. 2016), altitude (Bhambri et al. 2011), slope and aspect (Bhambri et al. 2011; Mehta et al. 2014), debris thickness (Pratap et al. 2015), glacier size (Mehta et al. 2014), glacier fluctuation (Chand et al. 2017), glacier dynamics (Deswal et al. 2017), topographic influence (Garg et al. 2017) and late-Quaternary landforms (Sharma et al. 2018). However, these studies explain in general the surface gradient as the main geomorphic element regulating the landforms and responses of the glaciers to climate change. However, a comprehensive study is required on glacio-geomorphic studies to connect natural resources with the livelihood of local people.

With glaciers being extremely sensitive to temperature changes, understanding their dynamics in the Himalayan ecosystem is imperative in order to study glacial and hydrological changes and its impact on the ecosystem and local community. It is also vital to understand and assess the impact of these changes on the livelihood patterns of the people who depend, directly or indirectly, on meltwater in the Himalaya and the foreland basins. Systematic availability of glacier and snow meltwater is necessary for irrigated crop cultivation in the Himalayan region (Nüsser and Schmidt 2017). Therefore, our geomorphological mapping focuses on the part of the Lahul Himalaya where glacial and livelihood resource mapping has remained absent. This paper focuses on livelihood resource mapping and glacial geomorphology, including glacial, paraglacial process along with slope processes that dominate the contemporary landscape in the Urgos watershed. The meltwater from the Menthosa glacier is the main source of the Urgos Nala, which supports agriculture of three villages, namely Urgos, Tingrat and Gompa. The effect of a small amount of glacier retreat and changes in seasonal snow cover is critical for the functioning of meltwater-dependent mountain communities (Nüsser et al. 2018). These large-scale geomorphic maps would potentially be used for several purposes such as preparing hazard maps for planning and nature conservation as well as for engineering works (Cooke and Doornkamp 1990) and to understand the dependence of vulnerable area population on natural resources.

Study Area

The Urgos watershed lies in the Lahul division of Lahul and Spiti district of Himachal Pradesh in the western Himalaya. It is located within the Miyar basin which is a sub-basin of Chandrabhaga basin (Upper Chenab). Geographically, the Urgos watershed extends between latitude 32°51′30.528″N–32°56′7.567″N and 76°42′41.604″E–76°49′45.164″E longitude (Fig. 1). The total area of the Urgos watershed is 54.31 km^2. The watershed is situated in the rain shadow zone of the Pir Panjal Range of the Lahul Himalaya, where western disturbances dominate with solid precipitation. The study area, however, is confined by towering peaks. The Menthosa is the highest peak (6448 m amsl) in this watershed. The collective impact of topographic elements may accelerate or delay the response of glaciers to climate change (Garg et al. 2017). Watershed topography, such as catchment area and slope, is an important element that affects surface waters and basin hydrology (Chen and Lu 2014; Khan et al. 2017). In the Urgos watershed, elevation varies from ~ 3160 to 4888 m a.s.l. and settlements exist between 3160 and 3400 m a.s.l, and glaciers are found above 4377 m a.s.l. The slope of the area varies in the watershed from 15° to 75°. Due to steep slopes, the upper and middle part of the watershed is highly dominated by snow avalanches in the winter months. Such accumulated avalanche cones serve as a source for irrigation for the local people in the summer months. The middle zone has massive debris deposits; mass movement processes of glacial and periglacial work dominate this landscape.

The Urgos Nala is a major source of water for Urgos, Tingrat, and Gompa villages situated at the lower valley of the watershed. Urgos village is situated at an altitude of 3281 m and is separated from Tingrat by the Urgos Nala while Gompa is located between these two. The Census of India 2011 reported 73 households in the watershed, with a total population of 324 persons.

Materials and Methods

Owing to the location of the glaciers in remote areas, conducting field-based studies and observing changes cannot be carried out on a regular basis. Therefore, applications of spatial information techniques such as geographic information system (GIS) and remote sensing in glacial geomorphology are now widely used in creating glacier inventories and mapping the distribution of landforms and sediments (Izagirre et al. 2018). In this watershed, all the existing landforms were mapped using various combinations of satellite images, digital elevation model (DEM) and Google Earth 3D visualization at the scale 1:5000. Remotely sensed satellite data along with DEM are very supportive in mapping geomorphological landscapes of glaciated and deglaciated valleys of the study area (Rashid et al. 2017). In the study area, the glacial geomorphology and societal resources were mapped through on-screen digitization based on visual interpretation at multiple scales in LISS-IV (5.8-m resolution), Landsat 8 (15 m panchromatic band and 30-m resolution) satellite images and images available on the Google Earth platform.

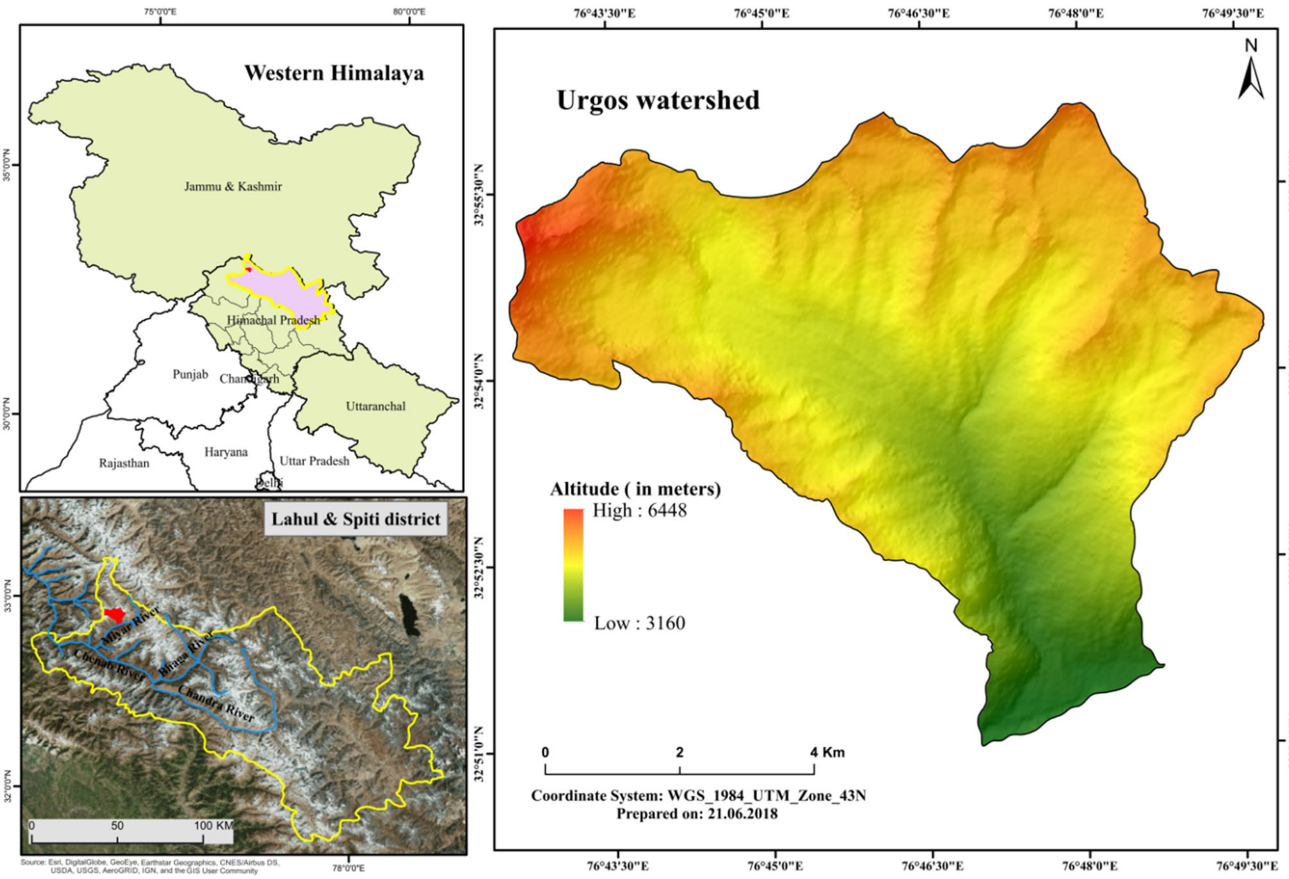

Fig. 1 Location map of study area in Lahul and Spiti district, India

The false-color composites of image bands were judiciously used for mapping. PAN image of the Landsat 8 resolution merges with the false-color composites images to improve spatial resolution. The Shuttle Radar Topography Mission (SRTM, http://srtm.csi.cgiar.org/) DEM with 30-m and high-resolution terrain corrected elevation data of Advanced Land Observing Satellite and the Phased Array-type L-band Synthetic Aperture Radar (ALOS PALSAR) (https://www.asf.alaska.edu) with 12.5 m spatial resolution were further used to map topographic and geomorphic features accurately.

The mapping of geomorphic features combined with the analysis of satellite images and information collected through regular fieldwork-based surveys was carried out during expeditions from 2013 to 2017. In this study, remote sensing information was directly linked with ground observations. Finally, terrestrial photographs and instrumental measurements were used as reference data to validate the geomorphic landforms mapped from the satellite images. Some glacial landforms were digitized in Google Earth Pro software as ‘kml-files.’ Furthermore, kml-files were converted to ‘shapefiles’ (shp) using the Global Mapper. During the process of mapping, two different feature datasets were created: (1) surficial map features (e.g., glacier ice, rock glacier, snow cover, glacial till, glacial valley, scree/talus, debris cones, bare bedrock, agriculture and settlements) which were saved as polygons and (2) linear features (e.g., arête, ridge, moraine, crevasses, streams, irrigation canal and road), which were very small to be digitized as polygons at 1:5000 scale and were, therefore, digitized and saved as lines features. Unique map symbols were given to small features such as Gompa (Buddhist Temple), Helipad, and schools because these features were too small to view on the map, but are significant indicators of the social development of the people in the watershed. Contours were overlain on the geomorphology maps at intervals of 100 m to show the exact elevation position. Final cartographic work and layout work were accomplished in ArcGIS software. Field measurements and photographic details collected in the study area are the most suitable source for validating and identifying the geomorphic features and up to certain extent to establish relative chronology. For example, rock glacier and recessional moraines in the upper and middle areas of the watershed appeared as a glacial till even on the high-resolution LISS-IV and images available on Google Earth.

These landforms were correctly mapped after ground-truth verification. After mapping of geomorphic features and resources, validation was carried out using DEM and field data. Furthermore, these features were classified as erosional, depositional landforms, natural and socioeconomic resources. Small, but vital features were mapped using Total Station (TS), Global Positioning System (GPS) and Differential Global Positioning System (DGPS). The Total Station was used to map the snout of Menthosa glacier. Due to main source of livelihood, a separate and detailed map of natural and socioeconomic resources was prepared. Finally, the geomorphic mapping and analysis were completed with reference to glacial and periglacial landforms, keeping in view the societal resource necessities in the watershed. The detailed methodology is illustrated in Fig. 2.

Results and Discussion

Depositional and Erosional Landforms

Evolution of landforms in an area primarily depends on the geology and climatic conditions of the region (Zwoliński et al. 2013). However, in the mountainous region glacial and periglacial regions have a dynamic and critical role in controlling local and global climate that in-turns modify the landforms. For that reason, accurate description and mapping of glacial and periglacial landforms and sediments are imperative. This information can be used as proxies to construct past glacial and glaciofluvial processes in the region. Four major landform categories were mapped in the area that include geomorphic, glacial, hydrological and socioeconomic features. The mapped landform indicates multiple glacier advances in the area. The major erosional landforms features existing in the Urgos watershed are glacial valley, hanging valleys, cirques, gorge, arête and ridges (Fig. 3). The glacial and glaciofluvial depositional landforms mapped are moraines, till, talus and debris cones. Geomorphic features mapped using satellite images are verified in the field which are listed in Table 1.

The glacial valleys were formed due to the advance and retreat of a glacier from its maximum extent. Sharma and Owen (1996) explained that glacial valleys are formed by sedimentation involving glacial, paraglacial and mass movement processes of deglaciation. Morphologically, a glacial valley contains U-shaped cross-profiles and with a trough-like shape. U-shaped valley of Urgos watershed reflects the widespread glaciation of the Lahul Himalaya in the late Quaternary. Only one deep and sharp gorge exists in the watershed, formed by glacial and fluvial processes (Fig. 4e). The middle zone of the watershed valley floor is

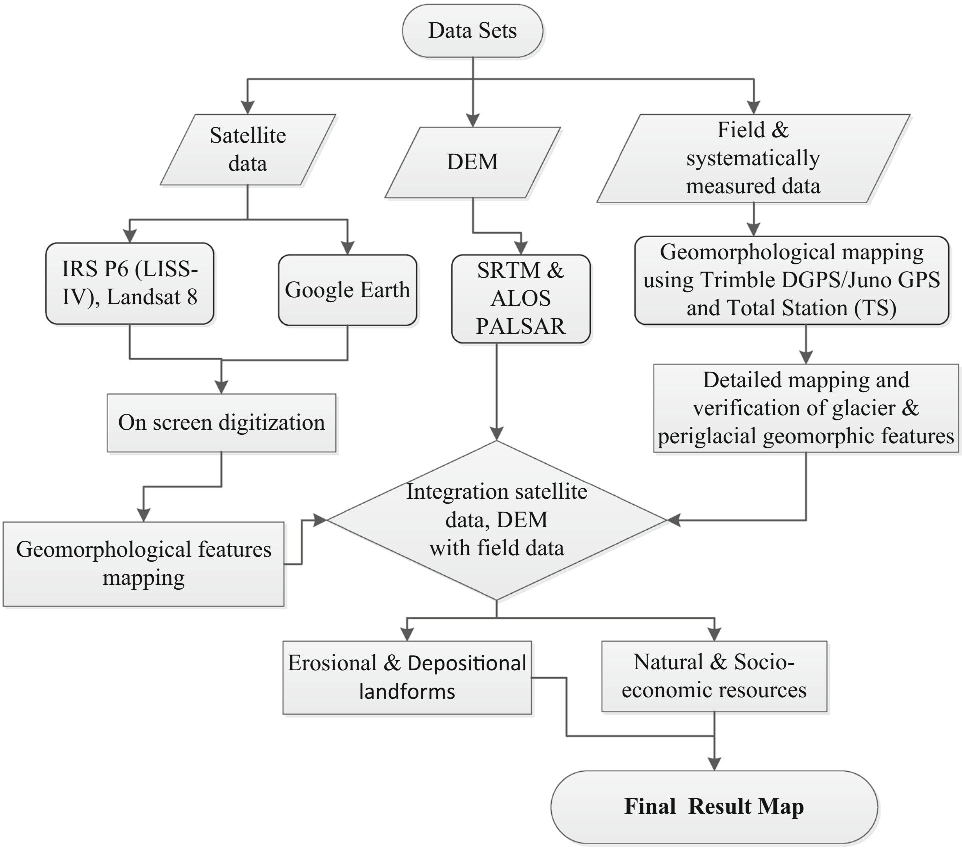

Fig. 2 Workflow of the glacial geomorphology and livelihood resources mapping in the Urgos watershed

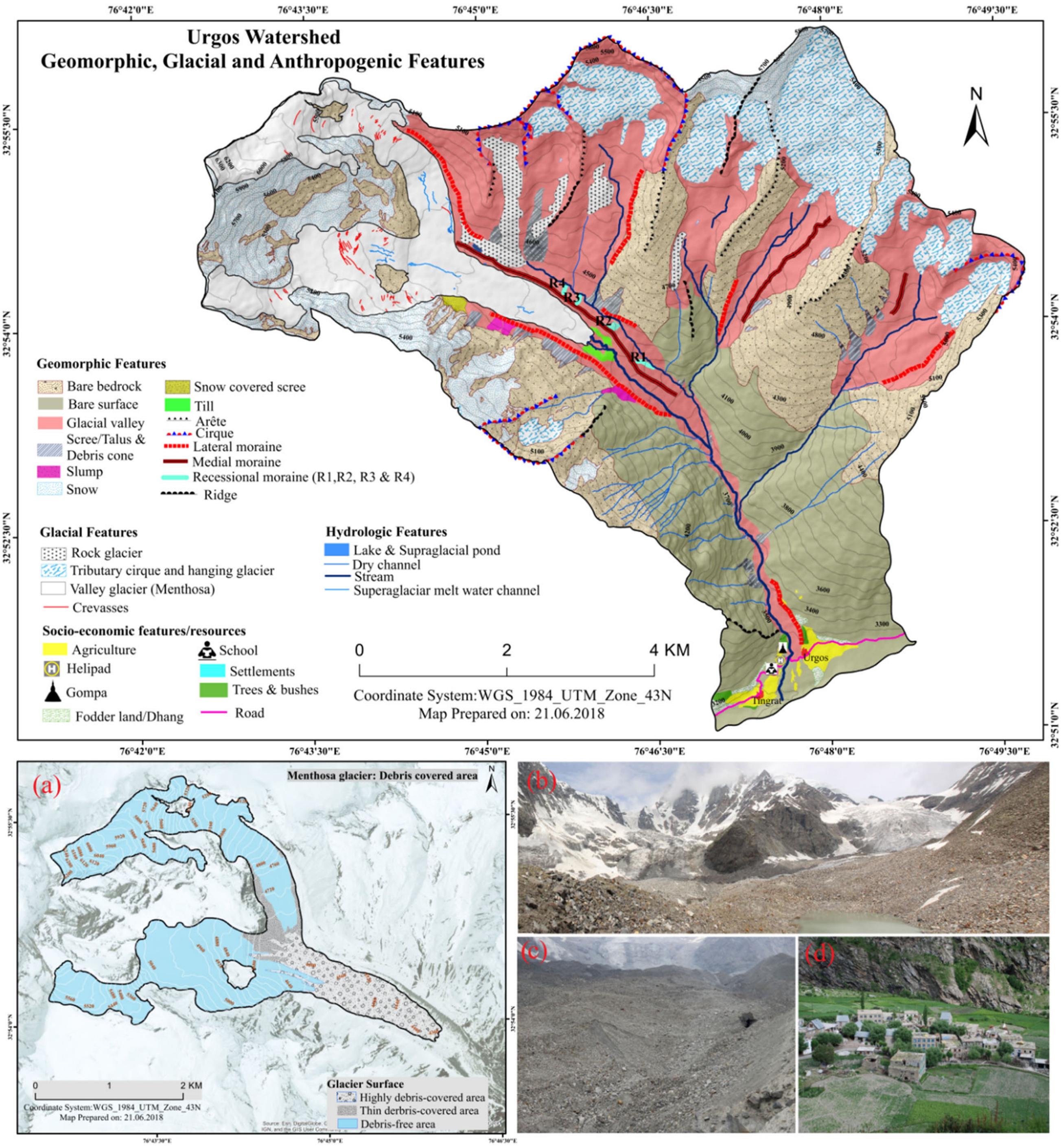

Fig. 3 Glaciological and geomorphology map of Urgos watershed based on LISS-IV, Landsat 8 and images available on Google Earth of September 24, 2014, September 28, 2014 and September 26, 2014 and field mapping. **a** Menthosa glacier debris cover map is based on the satellite images; **b** accumulation areas of the Menthosa glacier; **c** debris cover, ablation zone of the glacier; **d** Tingrat village

occupied by reworked outwash deposits and stream channels. This zone is covered with rock debris possibly formed by frost shattering in the areas.

The retreat of glaciers worldwide has uncovered large areas of glacial and subglacial landscapes and formed ice-marginal landforms such as moraines leaving behind extensive glaciofluvial deposits (Evans 2013). Different sets of lateral, medial and recessional moraines were mapped in the Urgos watershed. In the watershed, medial and lateral moraines are found parallel to the present Menthosa glacier. In the deglaciated valley of the watershed, a number of isolated patches of moraine are found at

Table 1 Area of different geomorphic and anthropogenic elements in the Urgos watershed

Geomorphic features	Area in km^2
Agriculture	0.384
Bare bedrock	10.685
Bare surface	11.09
Fodder, pasture and vegetation land	0.185
Glacial valley	12.624
Lakes and supraglacial pond	0.014
Rock glaciers	0.985
Scree/talus and debris cone	0.397
Settlements	0.026
Snow	5.132
Snow covered scree	0.053
Talus/scree	0.451
Till	0.061
Tributary cirque and hanging glaciers	6.204
Valley glacier (Menthosa)	6.005
Total	54.296

different altitudes that represent advance and retreat of glaciers in the past. A total of seven lateral moraines were mapped in the watershed. A prominent lateral moraine of the present glacier is ~ 2.9 km (Fig. 4b). This is a recently originated moraine in the ablation zone near the Menthosa snout, well preserved with perfect ridges and spread around the glacier margins. Another main lateral moraine with a length of ~ 1.01 km is mapped in the lower part of the watershed at an altitude of ~ 3300 m a.s.l. near Urgos village indicating the magnitude of extensive glacial extent during early Holocene which is constrained ~ 10–8 ka (Deswal et al. 2017). A corresponding lateral moraine from Karpat village, a little downstream from Urgos, has been dated to be ~ 8.5 ± 0.33 ka using optically stimulated luminescence (OSL) in this study.

A total of three medial moraines are present in the Urgos watershed. Prominent medial moraine runs parallel to the ablation valley and forms a prominent ridge down-glacier. It is a continuous ridge that extends ~ 3.7 km in length. Height and length of the moraine were measured by a topographic survey along the medial moraines of the glacier, using Trimble (R5) DGPS and a Trimble Juno 3D handheld GPS. The accumulation areas of both glaciers are almost next to each other and show a different pattern in glacier retreat. Steep mountain slopes confine both glaciers above ~ 4200 m (m.s.l) but narrow down in the accumulation areas. Irrespective of similar altitude, topography and climate conditions, both glaciers have retreated differently from last glacial maximum. Medial moraine of the Menthosa glacier extends at least ~ 3729 m down-glacier from the place of origin, from a huge dump probably a century old. The noticeable recent expansion is indicated by fresh erratics and boulders. The medial moraine is covered by slope debris with an average vertical height of 58–35 m (Fig. 4a).

Concretive recessional moraines across the ablation valley floor of the watershed are formed where a receding glacier remained stationary for long enough to deposit large sediments. Four recessional moraines are mapped within the limits of the lateral moraines, providing clear evidence of the stop–start-type retreat of the present glacier. Recessional moraines were identified and mapped during field surveys. These are small moraines ridges, parallel to the front of the glacier in the watershed (Fig. 4a). These small recessional ridges are restricted to 2.1 km distance limit from the glacier snout. Less debris has accumulated near the recessional ridges, indicating that the terminus of the glacier did not stay at one place for too long or meltwater quickly eroded deposits. In the watershed, recessional ridges have certainly been destroyed by fluvial, slope or periglacial processes. The geomorphic significance of recessional moraines can easily be adjudged as the best expressions of recessional history of any glacier.

The talus deposits in the study area are an inseparable element of the contemporary landscape of the area. In the Urgos watershed, debris cones have formed at many places, while talus is restricted to the base of steep cliffs. The recognition and characterization of talus slopes are important in determining the potential for landslides-related processes. In the glacier valley of the Menthosa, there has been continuous talus deposition along the valley wall between the altitudes of 4300–4800 m. This material is a massive deposition of frost-wedged angular clasts derived from the cold and dry valley wall parallel to the Menthosa glaciers.

Glaciers and Associated Features

Mapping of the outlines of the glaciers was done manually to differentiate glacier extent from snow cover, and clean glaciers from debris-covered glaciers. There are 16 glaciers mapped in the Urgos watershed from satellite images, covering an area of 13.19 km^2. Of the 16 glaciers, four are cirque glaciers which have an area of 1.78 km^2. The average glacier size varies from 0.083 to 6.004 km^2, with a mean size of 0.82 km^2. Though these glaciers are comparatively small, 13 glaciers that are < 1.0 km^2 cover a total area of 3.6 km^2 of the watershed. Six glaciers are hanging glaciers which cover 4.42 km^2 area of the watershed. The hanging glaciers are usually small in size, hang on a steep slope or terminate abruptly at the top of a cliff. Only the Menthosa glacier is a large valley glacier in the

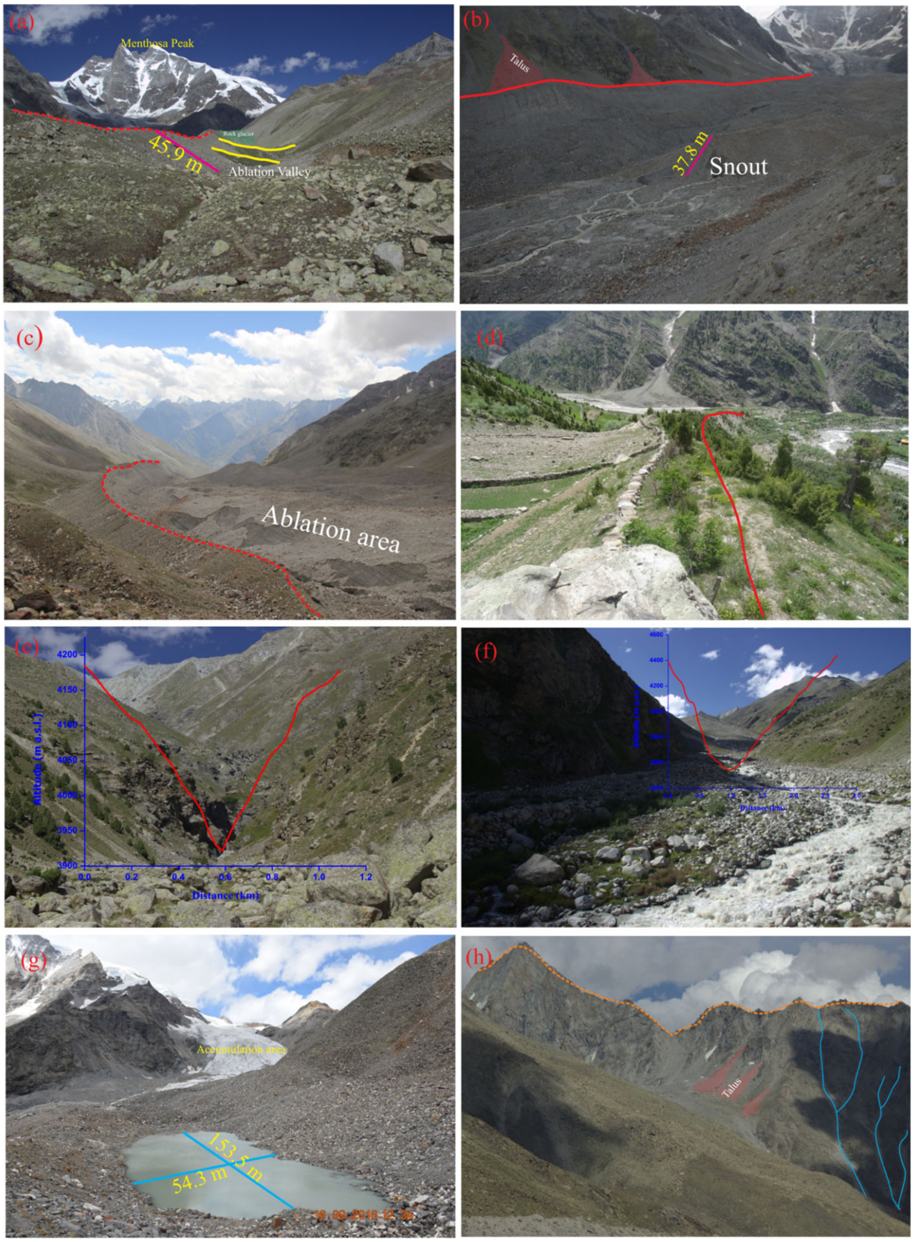

Fig. 4 Glaciofluvial landforms of the Urgos watershed. **a** ablation valley of the glacier, yellow lines mark shows the recessional moraines in the watershed, dashed red line represents the medial moraine and pink line represents the height of the medial moraine; **b** red line represents the lateral moraines and pink line shows the height of the snout of the Menthosa glacier; **c** dashed red line shows the medial moraine; **d** red line represents the lateral moraine near the Urgos village; **e** field photograph and profile show the gorge formed by the Urgos Nala; **f** field photograph and profiles show the U-shaped valley; **g** proglacial lake in the ablation zone of the Menthosa glacier; **h** dashed and blue lines show the arête and dry meltwater channels

watershed and covers an area about 6 km^2. A total of 19 supraglacial meltwater channels were mapped in the upper zone. This supraglacial meltwater channel plays a significant role in forming glacio-fluvial features such as pound, plains and supraglacial trough fills over the glacier. Ground verifications indicate that the snout area of the Menthosa glacier is covered by extensive and thick debris. The 1.11 km^2 and 0.32 km^2 area of the glacier is highly and thin debris covered, respectively, at different parts. It is proposed that thick debris cover may decrease the melt rates of the glacier. In the study area, crevasses were mapped for the Menthosa glacier using the visual interpretation of high-resolution satellite images. A total of 110 crevasses are mapped over the glacier indicating the high mass flux rate of the glacier and basement slope profile. These crevasses vary in length from 1 m to several meters.

A rock glacier represents an important element of debris movement from the base of steep slopes under a periglacial regime. Rock glaciers generally show steep slopes, well-defined lateral boundaries and an active and steep snout. A total of five rock glaciers have been mapped in the study area covering an area of 0.985 km^2. Individually, rock glacier area varies from 0.43 km^2 (largest area defined in the study area) to 0.09 km^2 with mean size of 0.22 km^2. In large-scale geomorphological mapping of small rock glacier, identification is not possible without proper field verification.

Total Station Mapping of the Snout

Robotic Total Stations (TS) (Trimble Sunnyvale S6, Sunnyvale, CA, USA), a combination of an electronic theodolite and electronic distance measurement device (EDM), are an accurate instrument for many glaciology surveying. To get X (easting), Y (northing) and Z (elevation) values from TS survey, the instrument must be situated within a reference system. This reference system can be either an arbitrary system or a known coordinate system (Lavine et al. 2003). The important measurements taken by electronic TS are slope distance, horizontal angle, and vertical angle. All other values such as coordinates are based on these values. The accuracy of the survey depends on relative positions and correct surveying procedures. The Total Station mapping of the glacier snout (Fig. 5c) and a detailed 3D diagram (Fig. 5a) were prepared using Terramodel software of Trimble. Using Total Station, the height, position and till accumulation near the Menthosa snout were measured. The maximum height of the Menthosa glacier snout ice face was measured at 37.8 m (2017).

Hydrological and Socioeconomic Setting

In the Himalayan region, receding glaciers result in the development and expansion of large and small lakes with tremendously high damage potential (Jain et al. 2015; Nagai et al. 2017; Osti et al. 2013; Prakash and Nagarajan 2017; Sakai and Fujita 2010; Yan et al. 2017). Due to climatic conditions and geotectonic settings, glacier lakes situated in the Himalaya are extremely prone to outburst. Approximately seven small supraglacial ponds and moraines dam lakes were delineated in the watershed covering 0.013 km^2 area. The Menthosa glacier has one proglacial lake in the ablation zone. The size of the largest moraine dam lake found in the watershed is 0.00748 km^2.

With the fluctuation in climate, socio-hydrology is more concerned with the people who are living in the cold desert of the Himalaya. Due to the remoteness, climatic and topographic barriers, societies inhabiting such high altitudes have limited access to resources and, therefore, come to depend overwhelmingly on natural resources. Therefore, to reduce the vulnerability of the inhabitants, we need appropriate mapping of the natural and socioeconomic resources in the region for the planning and policy implementation. The agriculture in the Ugros watershed was

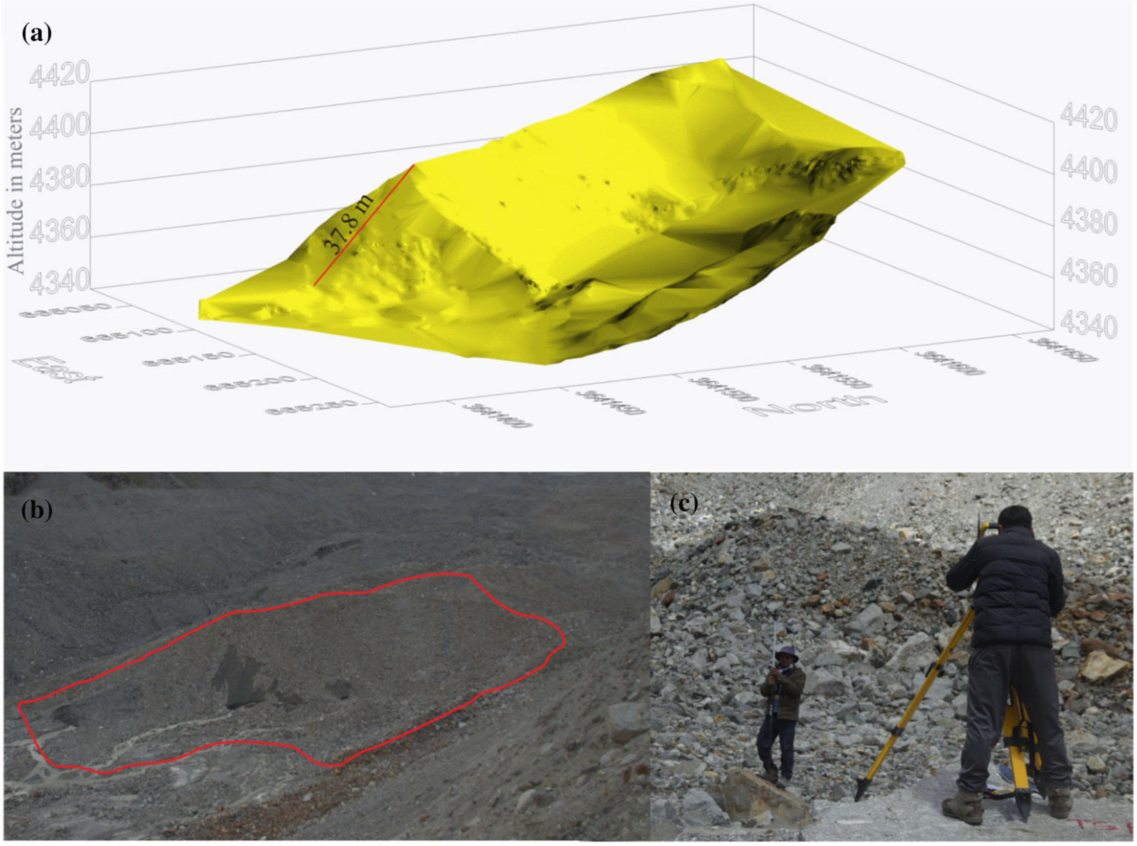

Fig. 5 Total Station map of Menthosa snout; **a** 3D surface diagram of Menthosa snout, red line represents the height of snout, **b** field photograph of the Menthosa snout, red line represents the area covered in TS mapping, **c** TS mapping of Menthosa snout

exclusively of subsistence nature until accessibility to the market; transport route was made available in the area in 1987. The agriculture of watershed is entirely dependent on snow, permafrost and meltwater from glaciers. They have irrigation canal (Kuhl) systems to harness water from snow and ice melt streams. In the area, it was observed that by using meltwater, a variety of crops were cultivated such as peas, seed potato, cauliflower, cabbages and sasouria lappa (*Kuth*) and inula racemosa (*Manu*). The high-resolution satellite images show that agriculture comprised 34.8 hectares, apple trees 0.14, pasture land 25.62, vegetation 8.88 and built-up 1.22 hectares out of a total of 5429 hectares of the geographic area of the watershed in 2014. In the watershed, agricultural fields have been developed on the river terraces and on the stabilized debris flow fans along either bank of the Miyar River (Fig. 6). The major vegetation types such as juniper, sea buckthorn (Himalayan berry) and willow trees are found in the watershed. The vegetation has great importance in the area; willow tree fulfills the need of fodder and fuel wood in this region. The decline in these plant species due to climatic variations and other reasons will inevitably affect the availability of fodder and fuel wood in the fodder and fuel-wood-scarce region. Therefore, it is necessary to map all the resources of the region to make the inhabitants of this region more adaptive to any changes.

Conclusions

This paper presents the first large-scale map in relation to livelihood resources in the Urgos watershed. The map is based on remotely sensed data with detailed fieldwork intended to present an overview of the high dependency of

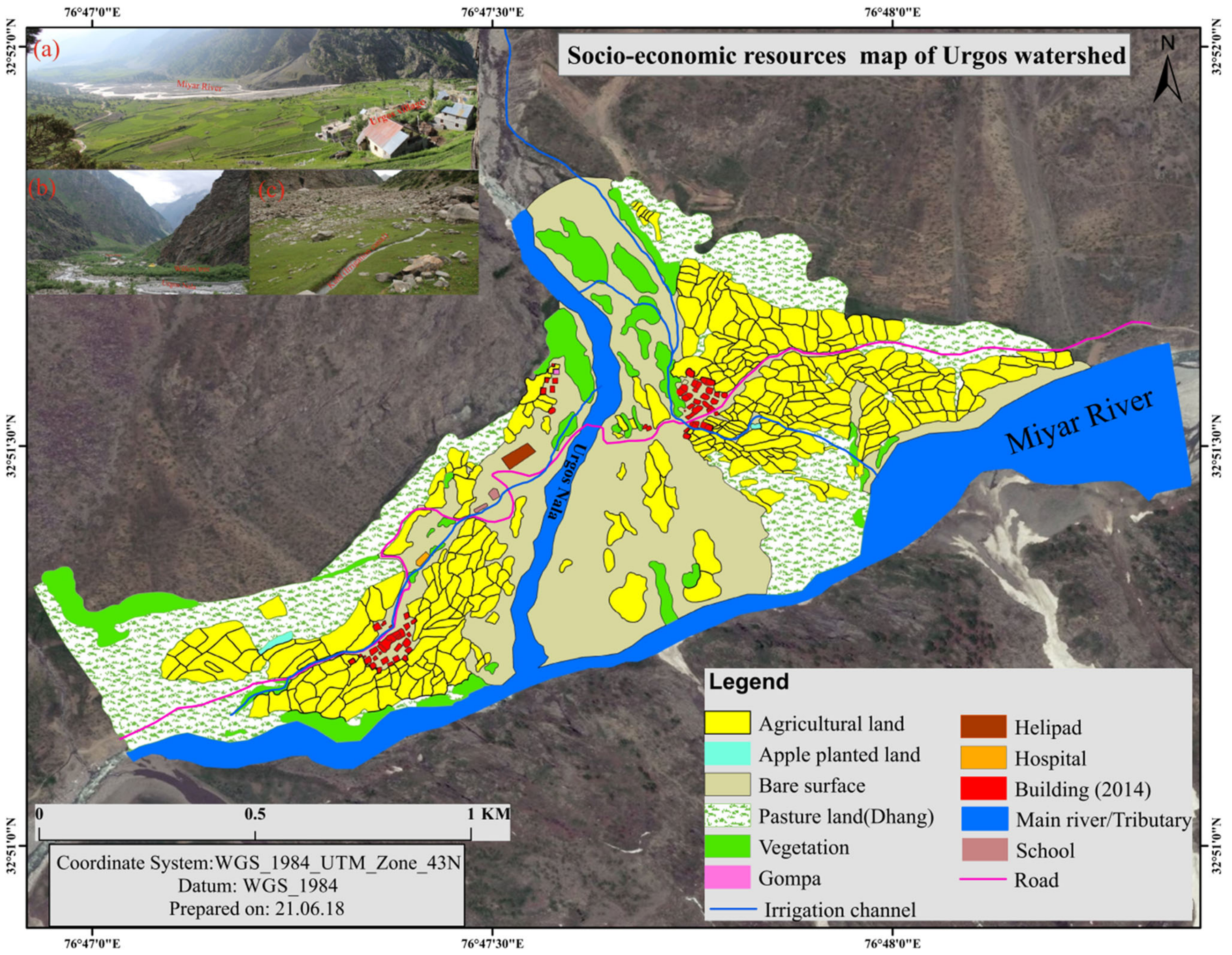

Fig. 6 Detailed natural and socioeconomic resource map of Urgos watershed based on LISS-IV and images available on Google Earth of September 24, 2014 and September 26, 14. Field photographs depict social aspect of the watershed; **a** Urgos village, Miyar River and agricultural field on river terraces and the stabilized debris flow fan; **b** willow tree, Urgos Nala and on the right side of the Nala are located Gompa and Tingrat villages; **c** irrigation canal

the people on natural resources. In the watershed, glacially modified landscape was mapped together with the human-modified landscape in order to get an estimation of the effect of glaciation and its impact on livelihood. The glacial–geomorphic landforms, recessional and terminal moraine, cirques and glacial trough observed in the valley helped in the rebuilding of the paleo-glacial setting of the region. Mapping of the watershed also indicates that landscape development is a product of intense glacial and fluvial activity in the past and present along with periglacial processes. In the study area, the interplay of glacial, periglacial and slope processes in combination with intense paraglacial reworking is clearly visible. The glacial lineaments, lateral and recessional moraines in the watershed indicate that possibly all of the watershed was covered by ice in the past. The mapping of the four recessional moraines indicates multi-cyclic landform evolution and multiple glaciations in the past. The changing locations of recessional moraines indicate the changing process over historical timescales. In the Miyar basin, based on the geomorphological signature, Deswal et al. (2017) established a stage named Miyar Stage, of maximum glaciation that predates the global last glacial maximum and traced up to Karpat village which is approximately 35 km from Miyar glacier snout and 8.5 km from the present snout of Menthosa glacier. The developments of longitudinal crevasses on the Menthosa glacier indicate a high melting rate of the glacier. The mapped area shows a complex landform which includes gorges, U-shaped valleys, debris cons and talus. The presented landscape signature shows that in the past, ice deposits and glacier extents have varied within the watershed. The livelihood resource mapping shows that in spite of enormous available land, the local people have limited suitable land to perform their economic activities. People living in the watershed are totally dependent on natural resources for their livelihood, and meltwater plays a very significant role in their livelihood pattern.

The geomorphology mapping was carried out at various scales for the final map. The various spatial resolution datasets used for mapping have possibly generated variation in mapping quality, mainly between areas covered by high- and low-resolution images. Furthermore, the complication of outlining the glacially reformed topography forms an imprecision at the large-scale landform mapping. Despite many limitations in data, it does not hinder the purpose of our mapping and approach which sought to combine natural resources with societal development.

Acknowledgements This work has been carried out as a part of the Inter-University Consortium on Climate Change (IUCCC) project, funded by the Department of Science and Technology, Government of India. S Prakash is thankful to the Department of Geoinformatics—Z_GIS, University of Salzburg, Austria, for providing research facility and infrastructure. Thanks to anonymous reviewers for constructive suggestions which helped us to improve the content of the manuscript.

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