JOURNAL INDIAN ASSOCIATION OF SEDIMENTOLOGISTS ISSN NO. 2582 - 2020
Vol. 37, Issue 2, 2020, pp. 141-147
DOI: http://dx.doi.org/10.51710/jias.v37i2.110

Impact of Elevation, Glaciations, Tectonics on landscape characteristics of the watersheds in Bhagirathi valley, Garhwal Himalaya

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Abstract

Terrain attributes of the watersheds were determined in the Bhagirathi basin, Uttarakhand Garhwal Himalaya, India. Spatial distribution of terrain attributes have been used to determine the impact of elevation, glaciations and tectonic processes on terrain characteristics of the watersheds. The results indicated that permanent snowline altitude bear direct relationship with numbers of watersheds. Degree of glaciation influences the area, slope, variation of elevation, profile and plan curvature surfaces and relief of the watersheds in the Himalaya. Hypsometric Integral of few glaciated watersheds indicated the active tectonism due to high bedrock excavation in the glaciated regions of Himalaya.

Keywords; ASTER DEM, Geomorphometry, Watershed character, Landscape, Bhagirathi Basin, Garhwal Himalaya

Introduction

The continuous Himalayan arc covered by the v aried geological, geographical and climatological conditions. It lead to the enormous diversity in geomorphological processes and provide a unique natural laboratory. Therefore, numerous field based

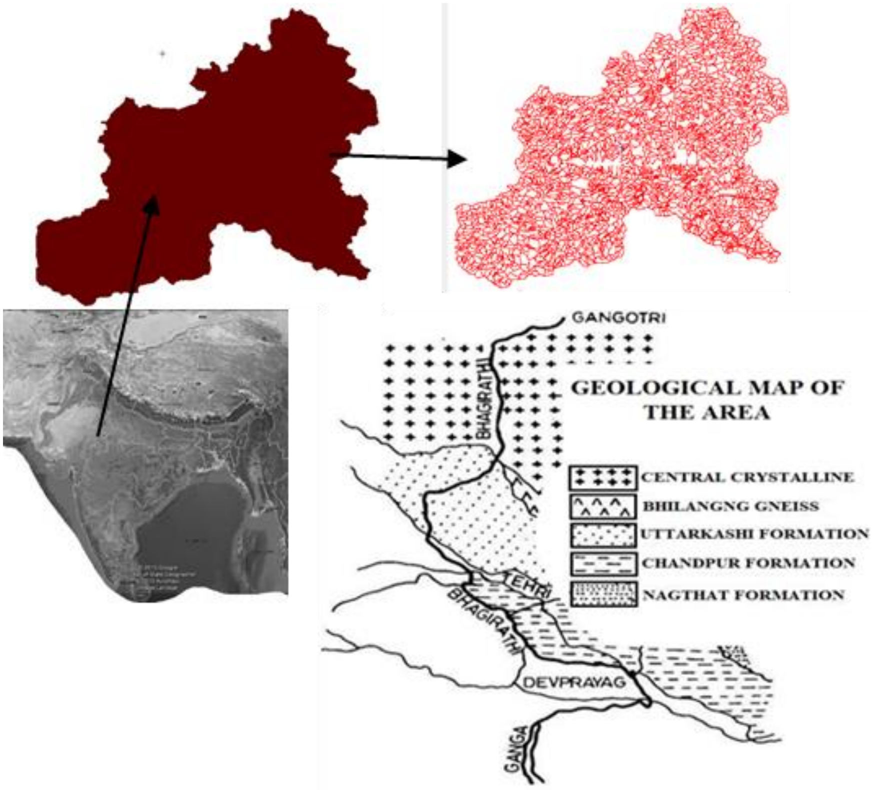


Fig. 1. Location and geological map of Bhagirathi river basin (after Pandey et al., 1999)

studies have been completed to envisage the relationship between the tectonics and weathering interaction in the Himalaya by conventional methods such as river terrace study in river bank cross section, drilling, trenching, seismic profiling, sedimentological studies, radiometric dating, glaciological studies, etc.

Table 1. Terrain parameters and their formulas

Parameter	**Formulas**
Slope	0-90 in degree
Standard deviation of elevation (STDE)	$\sqrt{\Sigma(x-\bar{x})/n}$
Relief	H_{max} -H_{min}
Hypsometric Integral	H_{mean} -H_{min}/H_{max}-H_{min}
Circularity Ratio	Re= 4π A/P^2
Plan curvature surface index	Second order polynomial (Zevenbergen & Thorn (1987)
Profile curvature surface index	Second order polynomial(Zevenbergen & thorn (1987)

Table 2: Stratigraphic succession and major rock types in the Bhagirathi basin

Vaikrita Group	Undifferentitive Vaikrita/Mandhall-Chandpur-Naghat formation	Purple Grey quartzite, grit and conglomerate, thin bedded limestone – phyllite/slate laminated greenish grey phyllite /slate with lenticular greywacke, purple green quartzite, grit conglmerate
Garhwal Group	Granite	
	Bering Formation	Quartzite with mafic volcanics
	---**Disconformity**---	
	Deoban Formation	Limestone-dolomite shale
	Rautgara Formation	Quartzite with mafic volcanics
	Uttarkashi Formation	Quartzite, mafic volcanic, dolomite - limestone, shale
Central Crystalline	Badrinath Formation	Garnet, Sillimanite, Muscovite and kyanite, migmatites, pegmatite and garnet amphibolite.
	Pandukeshwar Formation	Banded quartzite gneiss and interbedded quartz mica-schist, para-amphibolite
	Joshimath Formation	Garnet mica-gneiss, staurolite and Kyanite-gneisses, garnet amphibolite.
	Bhimgora Formation	White quartzite with gneiss and schist
	Ragsi Formation	Kyanite -mica-schist, gneiss, para-amphiboles.

(Thakur, 1995; Burbank & Anderson, 2001; Philip & Sah, 1999; Malik et al., 2003). In comparison to size and length of the Himalaya, the field based geological studies are very limited and isolated. These small scale studies cannot be generalized on Himalayan scale because of high geological diversity. In such scenarios the remote sensing images and geographical information studies (GIS) techniques provide better insight of earth processes. Altitude information is the first prerequisite to reveal any geological processes in a given landscape. The altitude information was made available through scanned topographic maps and GIS software for different parts of earth. But the restricted availability of the topographic maps of the Indian Himalayan region was a problem to the scientific community till the release of the Shuttle Radar Topographic mapping, Digital Elevation Model (SRTM DEM) in 2003 was made available. Hence, the altitude based studies in the Indian Himalaya were few in numbers (Agarwal, 1998; Asthana, 2012; Mishra, 1988; Singh and Singh, 1997). Now the free availability of DEM from ASTER, CARTOSAT, PALSAR remote sensing satellites supported by NASA, ISRO and JSA provide opportunities to visualize the landscape and compute geomorphometric parameters by various software (Tobias, B., 2004: Wang & Liao 2005; Burbank & Anderson 2001; Oguchi et al., 2003; Szynkaruk et al., 2004 ; Grohmann et al., 2007; Biswas & Grasemann, 2005 ; Robl et al., 2008; Goswami et al., 2012; Romshoo et al., 2012; Dortch et al., 2011; Amerson et al., 2008; Bali et al., 2012; Malik & Mohanty, 2007; Jordan, 2003). These studies used DEM information to support envisage the earth processes at small basins in specific areas of the mountains. Geomorphological processes and their mutual relationships on large scale can be revealed through analyzing the large area covering varied geological and climate conditions. In present study, the spatial distribution of the morphometric parameters of the watersheds have been analyzed to reveal the comprehensive interaction of earth processes shaping mountain system in the Himalaya.

Methodology

Morphometric analysis (Terrain Analysis) or geomorphometry is the practice of terrain modeling and ground surface quantification, through applications of earth sciences, mathematics, engineering, and computer science. Geographic information Systems (GIS) and Digital Elevation Models (DEMs) allow speed, precision and reproducibility of calculation for morphometric parameters. The ASTER DEM brought regional geomorphometric analysis in a fast and inexpensive mode in the present study. In this study, we have used raster format ASTER DEM-30 meter resolution data set for determining the terrain characteristics of watersheds in the Bhagirathi basin. ASTER DEM data have been assessed from USGS explorer and imported to PCI – Geomatica V.9.1.0 and watershed boundaries were created. The images for primary and secondary terrain attribute were prepared using Terrain Analysis System 2.9.0 and extracted on watershed basis using The PCI – Geomatica V.9.1.0 (Table 1).

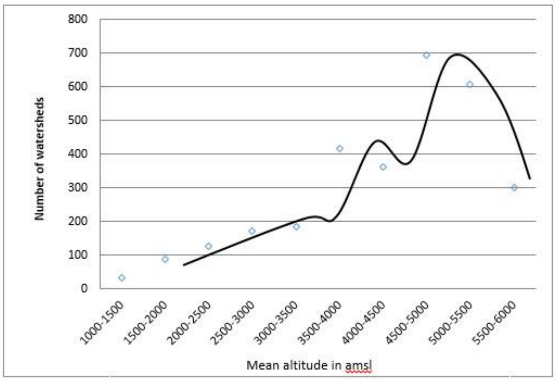
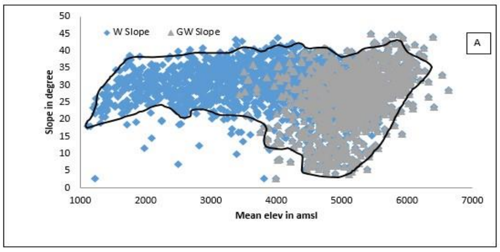


Fig. 2. Number of watersheds generation in different altitude zones.



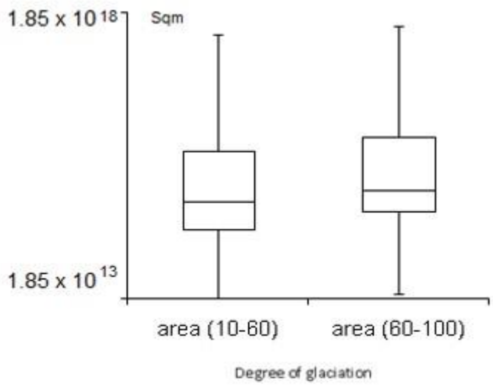


Fig. 3. Impact of glaciation on watershed area

Geology of the Area

Bhagirathi basin is one of the largest and most important parts of the Ganga System. It forms the mountainous catchment of the river Ganga. The Bhagirathi basin covers the Chaukhamba peak in the northeast of the basin. Geographically the catchment is bounded by latitudes 30^0 10′ to 30^0 30′ N and longitudes 78^0 10′ to 79^0 15′ E. The total catchment area of the basin is around 7811 km^2, out of which 2328 km^2 is snowbound. Geologically upper catchment of the Bhagirathi is mainly composed of rocks of Central Crystallines primarily consisting of schists, micaceous quartzite, calc-silicates, amphibolites, gneisses, granites, slates, and phyllites. In the middle and lower reaches, the Bhagirathi flow through limestone and dolomite bearing Uttarkashi Formation and before the confluence with Alaknanda river, it passes through phyllites and micaceous graywacke bearing Chandpur Formation (Table 2). The average rainfall varies between 1000 to 2500 mm/year of which 50–80% falls during the monsoon period between June and September. The Bhagirathi basin experiences strong seasonal variations, which is also clearly reflected in the monthly variation in stream flows. Maximum flow takes place during June-September when both rainfall and rate of snowmelt are at maximum (Bruijnzeel and Bremmer, 1989).

Results and Discussion

The land surface characteristics are the result of long term interaction of internal and external geological agencies and reflect in the landscape of a region. Changes in terrain characteristics due to earth processes may not reflect on average characteristics of the big basins. Therefore, morphometric parameters at watershed level have been studied across the Himalaya to observe the impact of various earth processes operative in various zones of Himalaya. These revelations has been unwrap using scatter diagram between watersheds morphometric parameters and mean altitudes of the watersheds across the Bhagirathi basin. A comparative analysis has also been conducted to determine the impact of elevation, glaciations and tectonic on morphometric parameters of the watersheds and their relationships. Watershed formation is the results of geological heterogeneity in an area. Therefore, distribution and size of watershed can be used to relate the environmental variability. The rate of watershed generation continuously increases from lower altitude range up to 2500 amsl and become stable from 2500 to 3500 amsl (Fig.2). A sharp increasing in numbers of watersheds has been observed from 3500 - 4000 amsl and 4500-5000 amsl. This increase is due to freezing/thawing processes operated during LGM (Last Glacial Maxima and present time respectively at respective altitudes. Number of researches have reflected the lowering of snowline in Bhagirathi valley during LGM and shifted to 4500 - 5000 amsl in present time (Sharma et al., 1996). At the lower altitude the fluvial processes are the main contributor and resulted in lower rate of watershed generation due to fluvial erosion and low relief. The increase in average area of watersheds with altitude has been correlated with degree of freezing in glaciations at higher altitudes. It is clearly reflected in box whisker diagram (Fig. 3) indicating that the mean area of watershed of fully glaciated regions is much more than that the moderately glaciated watersheds due to high excavation power of the glacier's ice (Amerson et al., 2008).

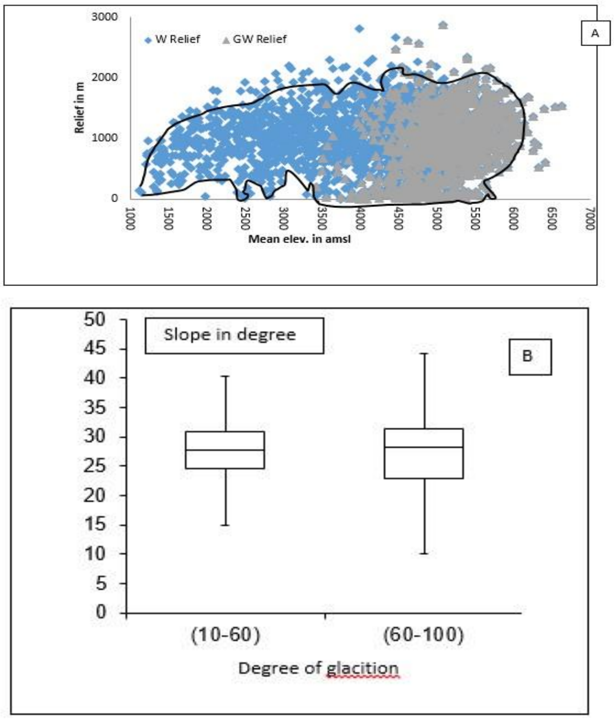


Fig. 4. Relationship between watershed slope and elevation (A), Impact of glaciation on watershed slope, (B) (*W slope for the non glaciated watersheds and GW slope for the glaciated watersheds).*

The scatter diagram (Fig. 4a) shows that the mean slope of watersheds increases with altitude from 1000 to 3000amsl and remains constant for the 3000-4000 amsl. High variation in mean slope of the watersheds at high altitude is resulting due to erosion from cirque and formationof arêtes and steep headwalls in glaciated region. Snowline in accumulation zone helps in bed rock excavation and result to the high slopes at high altitude. These high slopes are unstable and easily erodible and showing high variation in slopes than the lower altitude (Burbank et al., 1996). The box whisker diagram (Fig.4b) indicated that the lower slope values for fluvio-glaciated watersheds than that of fully glaciated watersheds. Fully ice covered glaciated valley is related to active bedrock excavation at snowline altitude that help to maintain the high slope near permanent snowline. It is also observed that lowest slopes are also related to high glaciations than the partially glaciated valley. This lowering of slope at high altitude range can be correlated with high glaciations (Bishop et al., 2003).

Watershed relief increases with altitude up to 4500 amsl and limited in higher altitude regions (Fig. 5a). The limitation of the relief of the watersheds is attributed to continuous crowing of snowline from LGM to present day (Brozovic et al., 1997) and result

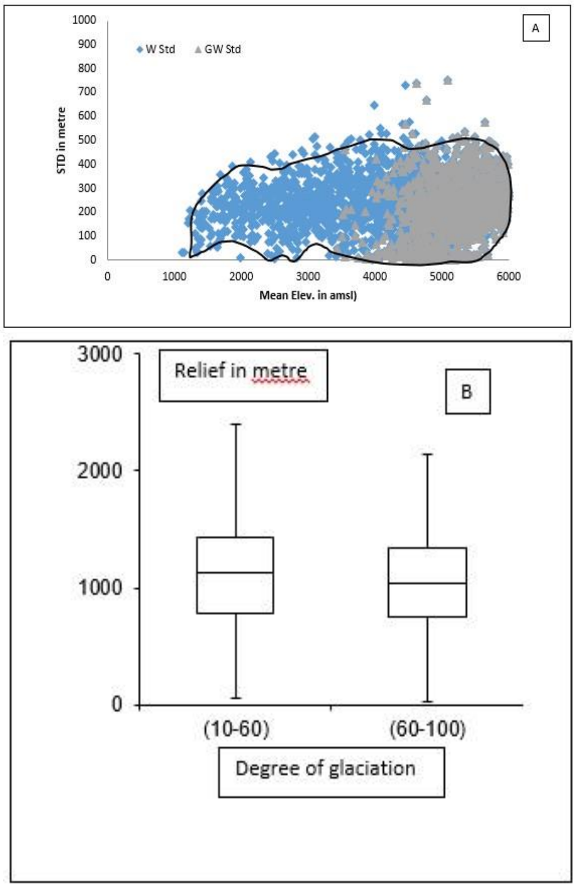


Fig. 5. Relationship between watershed relief and elevation(A), Impact of glacition on watershed slope (B). (*W relief for non glaciated watersheds and GW relief for the glaciated watersheds)*

in limited relief in areas of present and past glaciations at high altitude (Castillo and Salinas, 2013). In fully glaciated watersheds the thick ice acts an agent for leveling the terrain. The continuous erosion of rock material at snowline results in continuous rising of mountain to adjust rock mass and limit the relief in high mountains. A comparative analysis of partial glacial watersheds (glacio-fluvial) and fully glaciated watersheds suggests that the high deposition and removal rate of earth material flux assisted by melt water in partially glaciated watersheds is responsible for high relief. While, the only erosion and transportation in fully glaciated watersheds results in the limited relief in glaciated region at high altitude (Fig. 5b).

The scatter diagram between standard deviation of elevation in watershed and mean altitude

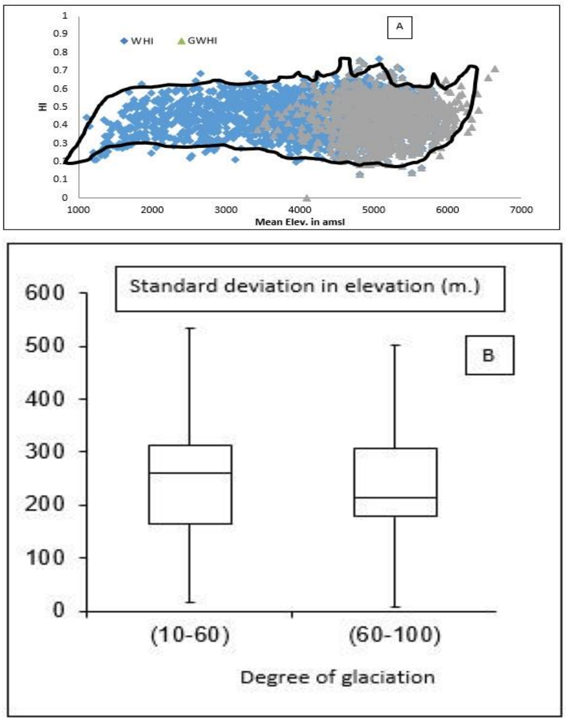


Fig. 6. Relationship between watershed elevation standard deviation of elevation (A), Impact of glaciation on watershed standard deviation in elevation (B). (*W std for the non glaciated watersheds and GW std is for the glaciated watersheds)*

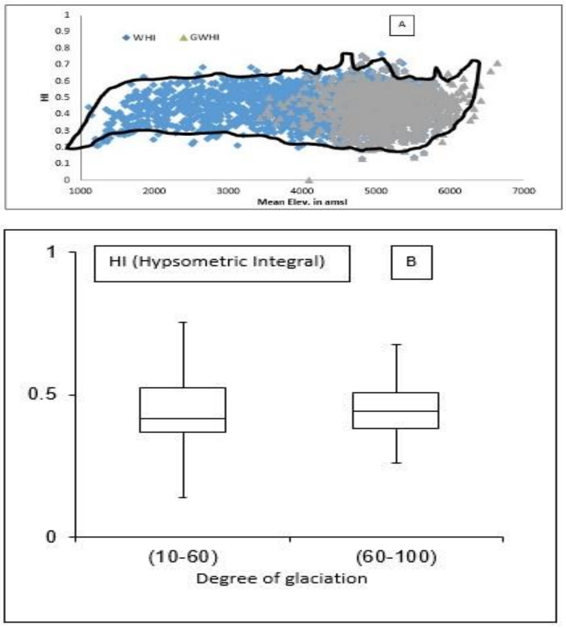


Fig. 7. Relationship between watershed elevation and Hypsometric Ingegral(A), Impact of glacition on Hypsometric Integral (B). (*W HI for the non glaciated watersheds and GW HI is for the glaciated watersheds)*

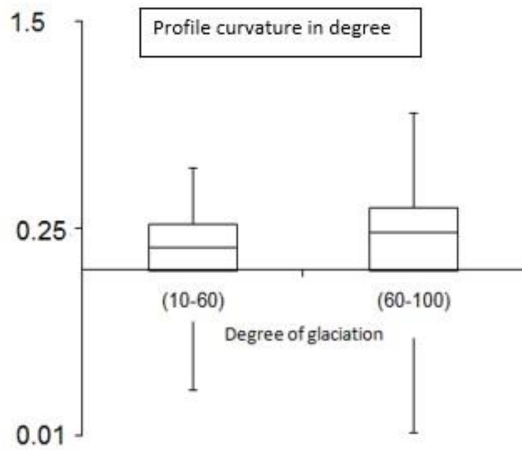


Fig. 8. Impact of glaciation on Profile curvature in Bhagirathi valley

(Fig.6a) very similar to the watershed relief distribution (Fig. 5a). It shows that watersheds with mean altitude are ranging from 4000amsl and above exhibit subdued topography indicating the maturity of the landscapes presented in the terrain due to active glacier excavation and transportation. However, higher STD of elevation in watersheds at lower altitude areas reflecting the rugged topography as a result of high degree of fluvial dissection processes associated with erosion and deposition in glacio-fluvial part of the watersheds. It is observed from box whisker (Fig.6b) that the watersheds of fully glaciated terrain are showing less mean standard deviation of elevation as compared to moderate or non- glaciated watersheds.

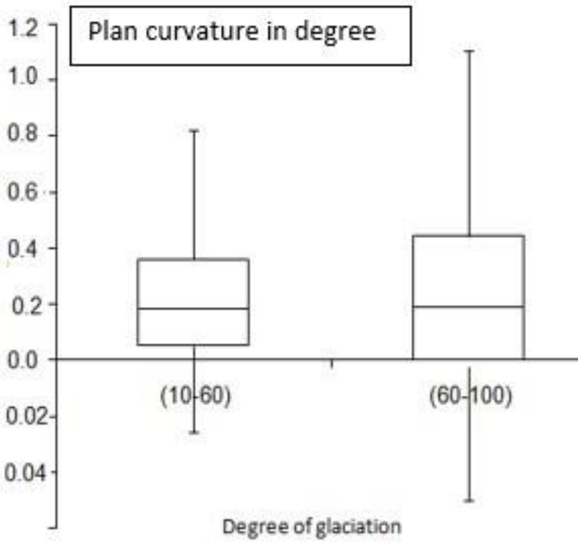


Fig. 9. Impact of glacition on Plan curvature of watersheds in Bhagirathi valley.

Hypsometry Integral (HI) is an important tool in revealing the tectonic activities using digital topographic data of a region. Brozovic et al. (1997) used the hypsometry of glaciated landscapes in the Nanga Parbat region to examine their response to varying tectonic uplift rates, and Montgomery et al., (2001) used hypsometry of watersheds to discuss the relative importance of fluvial, glacial, and tectonic processes along the Andes Mountain. The variation of HI values of watersheds with altitude indicates the sudden high variability at 4500-5000 amsl (Fig.7a). A sudden peaking of the HI values is related to tectonic activity near snowlines altitude due to imbalance in intense excavation of earth material in this zone in glacier areas. From box whisker (fig,7b) it is clear that low mean HI with high variations can be seen in the watersheds of moderated glaciations. These are the zones of maximum thawing and freezing processes that leads erosion and finally modification of watersheds. However, fully glaciated ice and snow covered watersheds have high mean HI with least variability. The most possible factor is that the extreme coldness in this zone prevents the modification of the watersheds and tectonic forces play important role in the formation of watersheds at high altitude.

Profile curvature surfaces control the water flow acceleration and deceleration and therefore, erosion potential in the area (Calogero Schillaci et al., 2015). In the Bhagirathi valley, the scatter relationship with profile curvature surfaces values and mean altitude of the watersheds does not shows any definite trend. However, the box whisker diagram reveals the impact of glaciations on the profile curvature surfaces of watersheds (Fig. 8). It shows that the spread of profile curvature surfaces indices and median index are much lower for partially glaciated watersheds than that of the fully glaciated watersheds. This suggests that glaciation favours the formation of concave profile surfaces in the watersheds.

Plan curvatures are horizontal surfaces which control over flow convergence and negative and positive values coincide with concave features and vise verse. The box whisker diagram (Fig.9) reveals that the watersheds with moderate glaciation possess more positive median value with less standard deviation than the fully glaciated watersheds. The fully glaciated watersheds encompass the complete ice surface i.e., these areas are the snow accumulation zones of the watersheds where convergent flow is somewhat dominant.

Conclusions

An assessment of terrain characteristics of the watersheds in the Bhagirathi basin, Central Himalaya suggests that formations of the watersheds are controlled by the snowline altitude in mountain regions. The relative average size of glaciatiated watershed is more than that of less glaciated watersheds due to high excavating power of the glaciated ice. Higher erosion power of glaciation is reflected in the lesser variation in standard deviation of elevation and in subdued topography in landscape of the region in glacier area. The relief is limited in higher altitude regions due to thawing and freezing processes accompanied by active transportation and deposition by active glaciations. Active erosion and deposition of rock material in the partially glaciated watersheds are responsible in higher variation in relief and standard deviation of the elevation. The tectonic imbalance produced by active glacier erosion near snowline altitude is reflected in high HI of some glaciated watersheds.

Profile and plan curvature surfaces of waterbeds do not show any systematic relationship with altitude. However, the relative contribution of fluvial and glacial processes can be distinguished by characteristics of the profile/plan curvature surfaces in high altitude Himalayan terrain.

Acknowledgements

The authors would like to express thanks to Chairman, Department of Geology, Aligarh Muslim University for providing the laboratory and library facilities. The authors would like to appreciate the financial assistance provided under DRS –II (SAP –I) program, UGC, Ministry of HRD, Govt. of India to conduct the present research work.

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