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IMPACT OF CLIMATE-TECTONIC INTERACTION ON TERRAIN CHARACTERISTICS OF THE WATERSHEDS IN WESTERN HIMALAYA

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Abstract: Terrain attributes of watersheds with elevation influenced by tectonics and erosion processes in the Himalaya. It is inference from the present study that glacier processes have influenced the generation of the numbers of the watershed, mean slope, surface curvature, plan curvature, shape complex index, standard deviation and relief in higher altitude. The tectonic variability is reflected by the Hypsometric Integral (HI) and relief of the watersheds at tectonic boundaries. However, mean surface curvature, plan curvature and shape complexity Index of watersheds doesn't show sensitivity towards tectonic variability. A sharpe increase in Plan curvature, Surface curvature and Shape complexity index values observed at altitude of 4200 m.a.s.l corresponding to glacier environment. High relief produced by glacier erosion near the permanent snow resulted in shadow in mountain valley during day time. Hence, low insolation causes slow de-glaciations processes and resulted in less sensitivity of big mountain valley glaciers towards climate warming. Relative intensity of the monsoon climate and global cooling by the glacial ages resulted in development of more southerly glacier basins in Himalaya.

Keywords; Digital Terrain Modeling, SRTM DEM, Gemorphometry, Terrain analysis, Himachal Pradesh, Himalaya.

1. INTRODUCTION

Himalaya provides a unique natural laboratory to analyze the impact of geology, climate, erosion and tectonic forces impact on geomorphometric properties of the landscape. Hence, numerous field based studies have been made to develop such relationship between the tectonics and morphology in the Himalaya and various other tectonic zones by conventional methods e.g., river terrace study in river bank cross section, drilling, trenching, seismic profiling, and sedimentological studies, radiometric dating etc. (Thakur, 1995; Burbank & Anderson, 2001; Philip & Sah, 1999; Malik et al., 2003). These techniques are costly/time intensive and need the sampling, analyzing and confirmation. Therefore, terrain studies are few in numbers because of the rugged terrain and logistic problems. In compare to size and length of the Himalaya the large scale geomorphic studies are very limited due to absence of elevation information. The spatial information of elevation change is a prime requirement of the geomorphologic studies. Conventional elevation information is made available through scanned topographic map and GIS software various part of the earth. But the availability of DEM (Digital Elevation Model of the Himalaya region had problem to the scientific community till the release of the SRTM (Shuttle Radar Topographic mapping) DEM in 2003. Therefore, the topographic based DEM studies conducted in the Himalaya are few in numbers (Agarwal, 1998; Asthana, 2012; Mishra, 1988; Singh &Singh, 1997). Now the free availability of SRTM DEM provides a unique opportunity to visualize the terrain and calculate geomorphologic attributes by software. Tobias et al., (2005) and Tobias, (2004) have used ASTER and SRTM DEM for studying Glaciers/Rock Glaciers and Geomorphology in Northern Tien Shan and Hindukush region. Wang & Liao (2005) have used SRTM DEM data for the water volume analysis in some reservoirs of China. Fault associate landforms recognition and tectonics activity were marked by (Keller & Pinter 1996; Burbank & Anderson 2001; Oguchiet al., 2003; Szynkaruket al., 2004; Grohmann et al., 2007). The elevation derived shadedmap and other terrain derivative maps(slope, aspect, Circulatory Ratio, Compactness factor and Hypsometric Integral etc.,) were also used to determine the factors responsible for geomorphological characteristics of the watershed in the Himalaya (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, Mohanty et al., 2004; Jordan, 2003). These studies were mainly related to identification of active fault, impact of neotectonics on change in landform, geomorphometric characteristics on hydrology, relationship between tectonic, glaciations and climate interaction. But these studies were conducted in specific area. Whole basins have not been studied from the point of full view ranging lower to highest altitude with various interaction of geomorphologic agents with altitude, climate and tectonics. However, it is needed to study the whole of the mountain range from lowest to highest altitude in Himalaya to decipher the interaction of various geomorphic agent, altitude dependent processes, climate and tectonic processes on landscape in a single entity and continuity. In present study Chenab river basin was selected to analyze the impact of tectonic - climate - erosion on morphometric parameters of watersheds in the Himalaya.

2. 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 release of Shuttle Radar Topography Mission (SRTM) DEM data (Rabus et al., 2003) brought regional geomorphometery analysis in a fast and inexpensive mode.

In this study, we have used Raster format of void filled SRTM DEM-90 meter resolution data set for the evaluation of the terrain characteristics of watersheds in Chenab basin. Data sets are freely available from NASA’s website. SRTM DEM data was imported to software (TAS) Terrain Analysis System, Version 2.9.0 and images for primary and secondary terrain attribute were prepared. The PCI – Geomatica V.9.1.0 was used to generate the automatic watershed boundaries using Hydrological modeling. The PCI, 9.1.0 software used these watershed and mean values were extracted for the terrain attributes of slope, aspect, surface curvature, Plan curvature, tangential curvature, profile curvature, mean altitude, standard deviation, relief, hypsometry integral, circulatory ratio (Table 1).

3. STUDY AREA

The study area covers the Chenab basin in parts of the state of Himachal Pradesh (Fig. 1) and covering lower, middle and higher Himalayas (32^0 05´N to $33^0$18´N and $76^0$34´E -$76^0$55´). Fluvial and fluvial-glacial geomorphic processes dominate in watersheds in low and high altitude respectively in the study area.

4. RESULTS

The relative change in terrain of watershed characteristics with altitude is a reflection of the geomorphologic forces operating in particular altitude, basic rock types, structural and tectonic setup of the region and climate. It is observed that watersheds generate with low rate for the mean altitude ranging from 500- 2000 m.a.s.l and high rate of generation of watersheds was observed for the watershed with mean altitude ranging from 4000 m.a.s.l and above. However, the rate of watershed generation don’t show any change in rate with altitude ranging from 2000- 3000 m.a.s.l (Fig. 2). The watersheds with mean altitude ranging from 2000 -3000 are few in numbers due to old mature topography of the lesser Himalaya of Pre-cambrian age.

Table 1. Terrain parameters and their formulas

Parameter	Formulas
Slope	0-90 in degree
Aspect	0- 360 in degree
Standard deviation	$\sqrt{\sum(x-\bar{x})/n}$
Relief	H_{max} -H_{min}
Hypsometric Integral	H_{mean} -H_{min}/H_{max}-H_{min}
Circularity Ratio	Re= 4π A/P^2
Shape complexity Index	Perimeter/(2*sqrt(Area/PI)*PI
Plan Curvature Index	Second order polynomial (Zevenbergen & Thorn (1987)
Surface curvature Index	Second order polynomial(Zevenbergen & Thorn (1987)

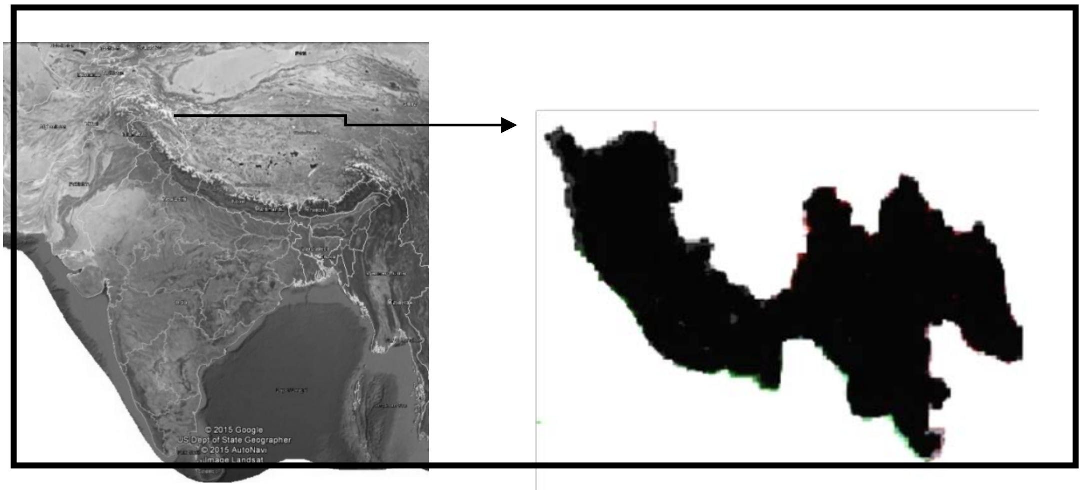

Figure 1.Location map of the study area

The watersheds with mean altitude ranging from 500 -2000 a.m.s.l, 3000-4000 m.a.s.l and 4000-6000 m.a.s.l have mean standard deviation of elevation is 261m, 404m and 270 m respectively. It is evident that the watersheds with mean altitude more than 4000 m.a.s.l are part of glaciated terrain and exhibits the subdued terrain compare to non-glaciated area and reflect in landscape (Millar, 1997). The high standard deviation exhibit by watersheds with mean altitude 3000 – 4000 m.a.s.l is related to active central Himalayan thrust (MCT) in this altitude band (Fig. 3).

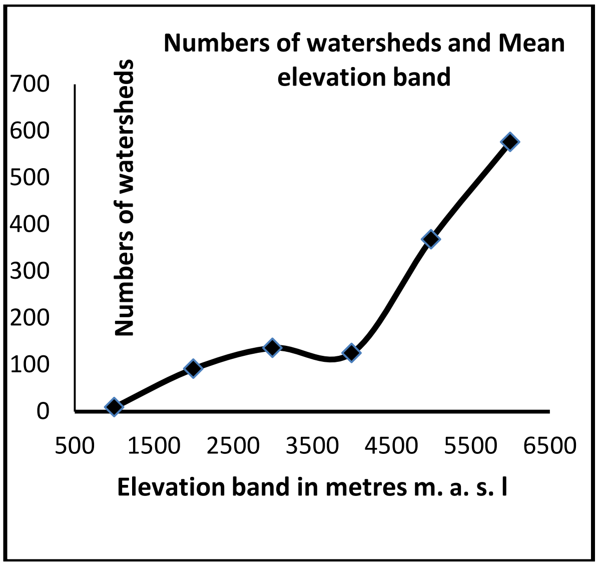

Figure 2. Generation of the watersheds in the Chenab basin

Average slopes of the watersheds with mean altitude ranging from 500 to 4000 m.a.s.l is 46^0 with standard deviation of 17^0. However, watersheds with mean altitude more than 4000 m.a.s.l have average slope of 48^0 with high degree of the standard deviation. Watersheds show high slope variability with altitude at 1500-2000 a.m.s.l, while the least variability is observed with watersheds have mean altitude between 2500 - 4500 m.a.s.l (Fig. 4). However, extreme values were observed for the watersheds with high attitude.

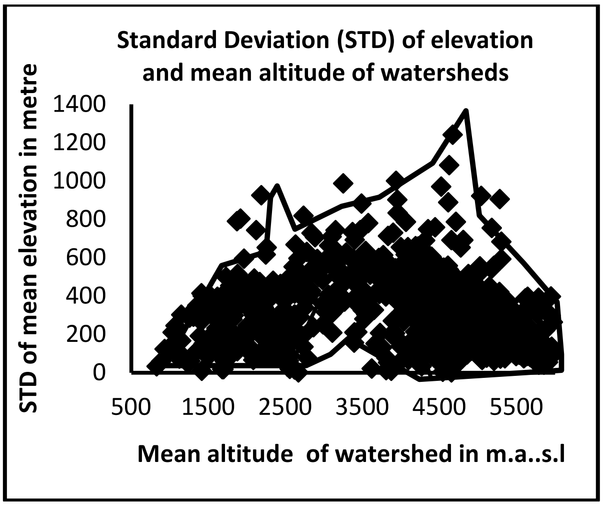

Figure 3.Relationship between mean altitude and Standard Deviation (STD) of elevation within watersheds.

The tectonic boundaries have important role in determining the aspect of the watershed. In the Chenab basin, most of the watersheds have mean aspect ranging from 100 – 350^0 from North. Watersheds with mean altitude less than 4000 m.a.s.l show average aspect of $213^0$and high standard deviation of 58^0 from North. However, the watersheds with mean altitude of 4000 m.a.s.l and above have average aspect of 203^0 and standard deviation 50^0 from North (Fig. 5). It is observed that the aspects of the watersheds with mean altitude ranging from 1000 – 2000 m.a.s.l changed suddenly compare to neighbors watersheds. This sudden change is possibly related to location of the MBT (Main Boundary Thrust) in Chenab basin.

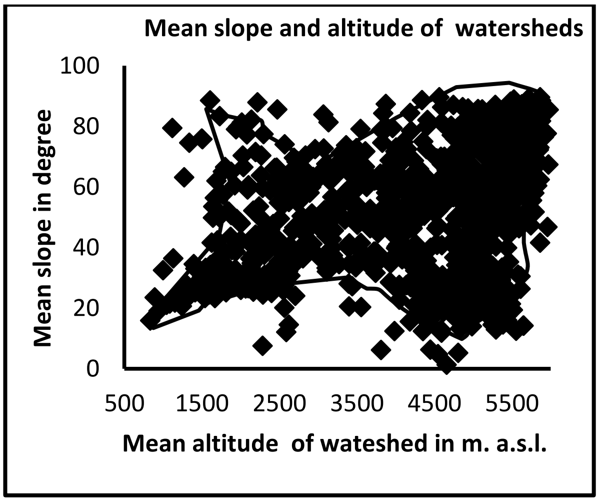

Figure 4. Mean slope and altitude of the watersheds.

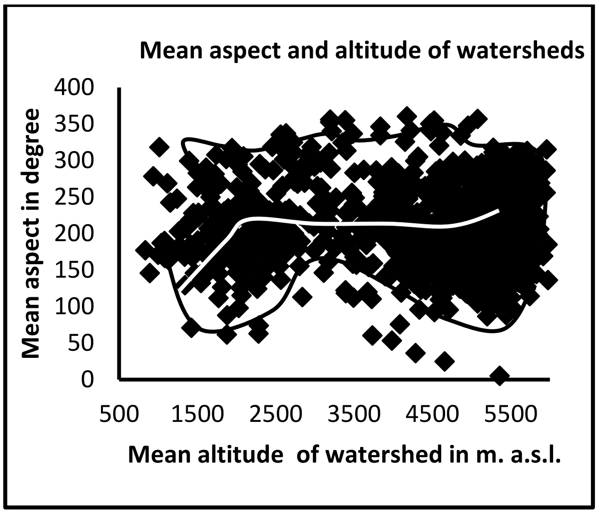

Figure 5.Mean aspect and elevation of watersheds.

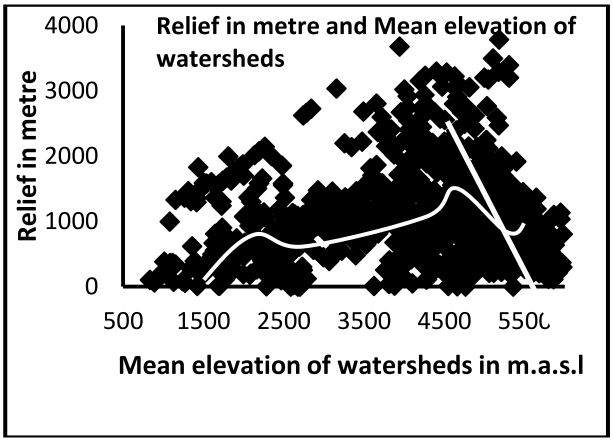

Figure 6. Relief and mean altitude of watersheds.

The relation between mean relief and watersheds′ mean altitude is presented in figure.6. It increases with altitude and attain maximum at 3500 – 4500 m.a.s.l and decreases further as the altitude increases. The anomalies of the relief have been also observed for the watersheds with mean elevation ranging from 1500 - 2000 m.a.s.l as a reflection of MBT (Main Boundry Thrust) in the region. Extreme relief is associated with watersheds situating in attitude ranging from 4500 to 5000 a.m.s.l. The frequency analysis indicates that 75 % of watersheds have mean relief under the 1500 meter and only 25% of the watersheds have more relief than the 1500 meter at higher altitude.

Hypsometry index (HI) of watershed has been used to study the influence of varying forcing factors on watershed topography. Low hypsometric integral values indicate that there is a small proportion of total basin area in the high elevation category. With increasing drainage area the importance of fluvial processes increase and the hypsometric curve becomes more concave and the hypsometric integral approaches zero (Goudie, 2004). The mean HI of watersheds and altitude relationship is given in figure 7. It is evident from the graph that it increases with altitude up to 1500 -2000 m.a.s.l and consistent moderate value for the watersheds with mean values from 2000 - 3500 a.m.s.l. At high altitudes the watersheds have high values with higher variability. The variation of HI values of watersheds with altitude indicates the sudden high variability at the altitude of 1500 - 2000 m.a.s.l and 5000 - 6000 a.m.s.l; these zones suggest tectonic and geomorphic boundaries respectively.

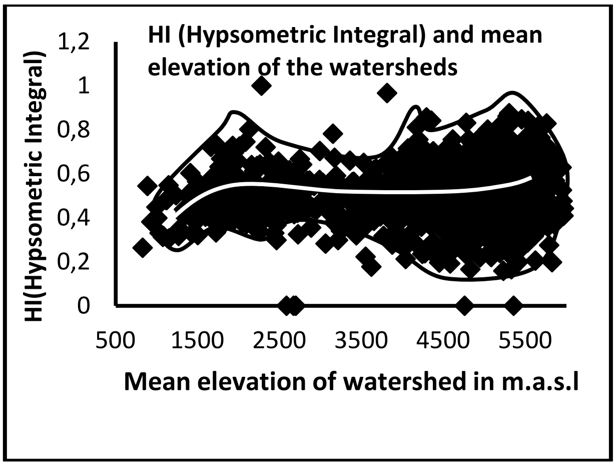

Figure 7.HI (Hypsometric Integral) and mean altitude of the watersheds.

The climatic, erosion and tectonic forces shape watershed and further the hydrology in region. The hydrological nature of the watersheds reflecte by Circulatory Ratio (CR). It is one of the important properties of the watershed and it varies between 0 and 1 (Kale & Gupta, 2001). The results suggest that most of the watersheds′ CR is close to 0.49 and 0.60 for the watersheds with mean altitude ranging from 500 – 4000 m.a.s.l and 4000 - 6000 m.a.s.l respectively. The mean circulatory ratio shows high variability up to 2000 a.m.s.l. However, least variability has been observed for the 2000- 3000 m.a.s.l and again shows high variability at higher altitude (Fig. 8). The low variability for the altitude ranging from 2000 - 3000 m.a.s.l is due to the mature topography of lesser Himalaya. It indicates that the majority of the watersheds are varied in nature from elongated to circular form for the altitude band of 500 - 2000 a.m.s.l. The higher CR in higher altitude indicates that most of the watersheds have slightly elongated in this region. In high altitude area the circularity ratio has been enhanced by broadening of glacial valley during glacial movement. Therefore, the watersheds from time to time experience high peak water discharges due to bursting of the supra glacial and englacial water bodies (Chopra et al., 2005). Delineating the sub-basins on the basis of higher values of these indices can becomes an important tool to decipher the areas prone to short high peak flows during flash floods (Bali et al., 2012).

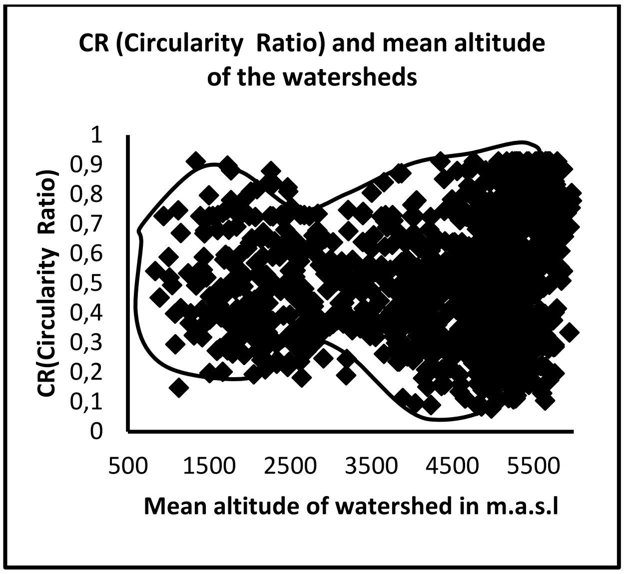

Figure 8. Relationship between CR (Circularity Ratio) and watersheds′ mean altitude.

Mean Surface Curvature, Plan Curvature and Shape Complex Index (SCI) of the watersheds and mean altitude of watersheds relationships are presented in figure 9, 10, and 11. It shows that watersheds with mean altitude values ranging from 500 meter to 4200 meter m.a.s.l have surface curvature values close to zero. At the altitude of 4200 m.a.s.land above onwards the surface curvature values become more positive revealing that the watersheds becomes more convex from the altitude of 4200 meter m.a.s.l and onwards. It indicated that the watersheds at lower altitude represent concave spur and convex spur at higher altitude. A sudden change in curvatures and shape complex index suggests a complex glacio/fluvial and tectonic active region. The convex spurs at higher altitude represent accumulation of materials along moraines in glaciated area.

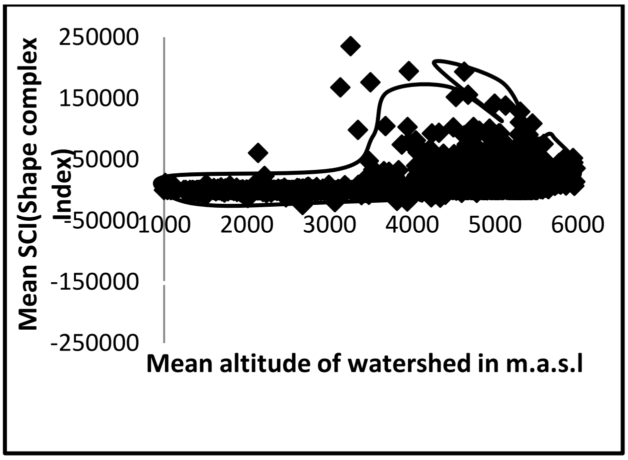

Figure 9. Mean Shape Complexity Index (SCI) and watersheds′ mean altitude.

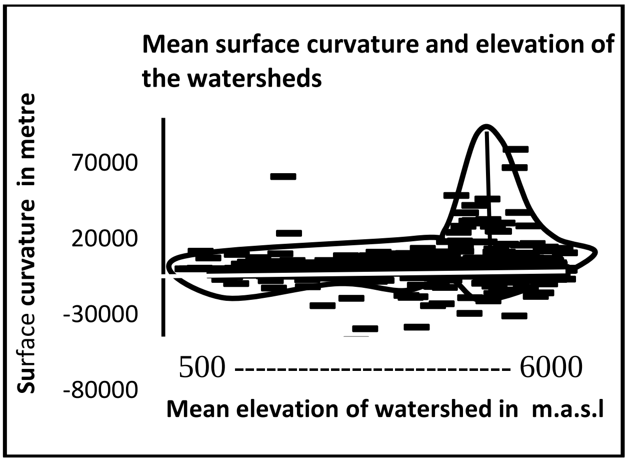

Figure 10. Watersheds′ mean surface curvature and mean altitude.

5. DISCUSSION

A comparative analysis of the watersheds characteristics along longitudinal cross section of Himalaya suggests that generation of the watersheds at high altitude is related to freeze and thaw processes which result in formation of local depression and further develop as watershed.

However, fluvial processes at lower elevation involve the movements of water which assimilate the local depression and form the bigger and few watersheds in lower altitude compare to glacier regime at higher altitude. Maximum numbers of the watersheds development at 4000- 5000 m.a.s.l coincides with regional permanent snow line (Dobhal& Kumar, 1996). The snow freez/thaw processes help in initiating basins formation at this altitude zone. The study conducted by Brocklehurstet al., (2004) has also shown a change in number of watersheds distribution from non-glacial to glacial basin transition from eastern Sierra Nevada to California.

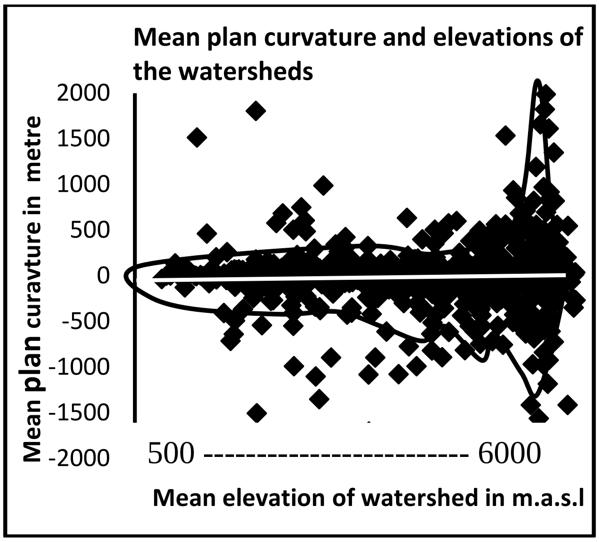

Figure 11. Watersheds′ mean plan curvature and mean altitude.

River-glacier as a geomorphic agents produce relief through weathering processes. The glacier is strong in plucking and erosion of the country rocks. Therefore, the standard deviation of the elevation distribution within watershed decreases as 4000 m.a.s.l onwards and minimum standard deviation of elevation is observed for the watersheds situated at high at altitude. Watersheds' relief increases with altitude only up to 4500m.a.s.l and afterword the relief is limited. The limitation of the high relief with altitude in the Himalaya is concur with Brozovic et al., (1997) observation and suggests that glaciations can limit relief up to some altitude near the Equilibrium Line Altitude (ELA). However, some extreme relief is associated with mean watersheds attitude ranging from 5000 m.a.s.l and above at high altitude due to cold climate of ridges and tectonic upliftment in the region. In glacier watershed the erosion by snow and ice at ELA help in bedrock erosion. It results in further uplifting of cirque region of glaciers and resulting high slopes in the watershed at higher altitude. Hill slopes of more than 45^0 tend to be eroded rapidly not only by shallow failure, but also by bedrock erosion as observed by Burbank et al., (1996). Higher slope of watersheds at high altitude subject to cold glaciers activity (Bishop et al., 2003). At higher altitude the periglacial and glacial activity results in lowering of the slope of the watersheds in active upliftment area which also caused high convex profile and surface curvature (Katsube & Takashi1999). In concurrent of these finding the surface, plan curvature and shape of watersheds do not show and systematic change along the altitude except high values and high variability at 4500 – 5000 m.a.s.l corresponding to ELAs and limits of the glacier basins′ erosion at high altitude. The high relief along with high slope generated by glacier erosion near snowline plays an important role in glaciations processes; it helps in snow accumulation and mobilization as avalanches and contributes to the glacier mass. High relief also creates shadows on glacier surface which inhibit the direct solar radiation on glacier surface and results in slow de-glaciation processes in high relief areas. Studies conducted by (Ahmad & Islam, 2011; Rathore, et al., 2009) show that the frontal valley glaciers show higher degrees of de-glaciation, while inner valley glaciers e. g., Gangotri, Pin-Parbati glacier show less rate of de-glaciations. The Glacier mass balance study conducted by (Julie et al., 2012), in Nanga Parbat also showed that the glaciers situated in high relief areas are either stable or minor thickening. Nanga Parbat area has highest relief in Himalaya, hence they are least affected by global warming than the glaciers situated in low relief areas. The snow and ice mass gain by these glaciers in recent is probably through warmed avalanches on glacier surface which might have led to positive glacier mass balance in recent years.

The more removal of material from the basins through glacier transport along with incision by the drainage resulted in imbalance of Iso-static forces and resulted in high relief in higher Himalaya (Molnar & England, 1990). The terrain attributes impact on weathering rate and hence, the relationship between altitude and weathering is also assessed. It indicated that the material excavation and transportation increases with altitude (Fig.12).

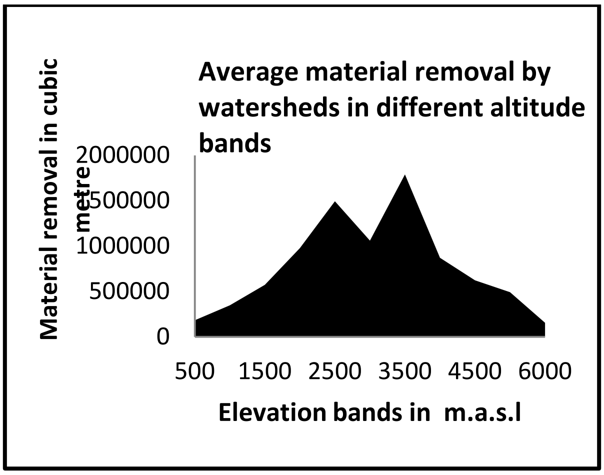

Figure 12. Average material removal from the watersheds in different altitude bands.

Higher physical weathering or mass removal at higher altitude is related to glacier weathering, which is more powerful agent of excavating the material from the watersheds. It has shown that maximum removal of rock material taken place at 2500 - 3500 a.m.s.l, which is near the regional ELA observed in Last Glacial Maxima period (Owen et al., 2002; Berthier et al., 2007). The average rock removal by each watershed is almost double in glacier activity zone than the watershed located in fluvial dominated area with mean altitude 500 – 2500 a.m.s.l. It indicated that the glacial processes operated since Pleistocene period have played a crucial role in shaping the Himalaya (Owen et al., 1995; Owen et al., 2002; Yang et al., 2002).

The watersheds characteristics in the Himalayas are influenced by the aspect due to snow storage, ice sensitivity to solar energy and direction of monsoonal precipitation. It is observed that the watersheds at higher Himalaya are more southerly than watersheds in lower altitude. Southern aspects of watersheds receive more energy from sun and also more precipitation from South West Indian monsoon. Therefore, high monsoon activity has led to more erosion on southern faces and fully development of the big watersheds in non glacial periods. The studies also suggested that glaciers situated in central and eastern Himalaya receive substantial precipitation during the summer monsoon (Fujita & Ageta, 2000). However, development of the glacier due to increased summer precipitation is considered minimal because monsoon intensity was reduced at Last Glacial Maxima time in Pleistocene period. In this period increased winter, westerly precipitation also did not provided the sufficient snow to expand the glacier in western Himalaya (Benn & Owen, 1998). Therefore, development and expansion of southern and eastern face glaciers in the Himalaya have resulted from regional cooling, which reduced ablation during the summer period and accumulation of monsoon snow protected the winter snowfall in ablation areas. Thus, effective precipitation has been increased, resulting in positive glacier mass balances and development of new glacier or advancement in Last Glacial Maxima in the old fluvial watersheds.

The active upliftment of Himalaya due to glacier erosion at ELA (Molnar & England, 1990), extrusive flow of Tibet to South (Burchfielet al., 1992) and Northward migration forces shaping the watersheds in the Himalaya. These forces are reflected in sudden change in HI and relief. The low HI ratio in lower basins is related to fluvial activity, which has deepened the valley. While, at higher altitude high HI values are related to glacial activity, resistant bedrock and active tectonics. The variation of watersheds′ HI ratio and relief with altitude indicated the sudden change at the altitude of 1500 - 2000 m.a.s.l and high variability at 4000 - 4500 m.a.s.l onwards indicated zones of tectonic –climatic boundaries and tectonic adjustment due to mass removal of glacier activity near the permanent snowline.

6. CONCLUSIONS

Systematic change of terrain attributes of watersheds at various altitudes present a synergic interaction of geomorphologic forces and tectonic-structural setup of the region. The glacier and periglacial processes generate numerous small basins and show comparatively less standard deviation of elevation within basins. The synergetic of the glacier erosion and upliftment results in glaciers ‘controlled relief and slopes of the watersheds. High relief generation in glacier valley responsible for shadows on glacier surface which inhibit the direct solar radiation on glacier surface and results in slow de-glaciation processes of glacier in inner mountain valley.

The glacier and non glacier glaciers watersheds processes results do not show any systematic change in surface curvature and plan curvature along the altitude except high variability at 4200 m.a.s.land onwards at corresponding to ELAs and upper limit of the glacier basins. High variability of curvatures at higher altitude, slopes, relief resulted in high shape complexity index and consequently circulatory ratio result in variable hydrological, glaciological responses for a given climate changes.

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REFERENCES

Agarwal, C. S., 1998. *Study of drainage pattern through aerial data,* Indian Journal of Remote Sensing 26, 4, 169 – 175.

Ahmad, S. & Islam, Z., 2011. *Control of terrain on de-glaciation pattern in Himalayas: A case study of glacier shrinkage in Himachal Himalayas,* Asian Journal of water, Environment and Pollution. 8, 1, 81- 85.

Amerson, B. E., Montgomery, D. R. & Meyer, G., 2008. *Relative size of fluvial and glaciated valleys* *in central Idaho,* Geomorphology 93, 537–547.

Asthana, A. K. A., 2012. *Landform evolution of the Nayar basin Garhwal Himalaya, Uttarakhand,* Himalayan Geology, 33, 1, 71-82.

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

Bali, R., Agarwal, K., Nawaz Ali S., Rastogi, S. & Krishna, K., 2012, *Drainage morphometry of Himalayan glacio-fluvial basin, India:hyddrologic and neotechtonic implications,* Environ Earth Sci 66, 4, 1163-1174

Berthier, E., Arnaud Y., Rajesh K., Sarfaraz A., Wagnon P., &Chevallier P., 2007. *Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India),* Remote Sensing Environ. 108,3, 327-338.

Bishop, M.P., Shroder Jr., J.F., & Colby, J.D., 2003. *Remote Sensing and Geomorphometry for Studying Relief Production in High Mountains.* Geomorphology, 55, 345-361.

Biswas, S. & Grasemann, B., 2005, *Quantitative morphotectonics of the southern Shillong Plateau (Bangladesh/India).,* Austrian Journal of Earth Sciences, 97, 82 – 93.

Brocklehurst, S. H. & Whipple, K. X., 2004, *Hypsometry of glaciated landscapes,* Earth Surface Processes and Landforms, 29, 907-926.

Brozovic, N., Burbank, D.W. & Meigs, A.J., 1997. *Climatic limits on landscape development in the Northwestern Himalaya,* Science, 276, 571–574.

Burbank, D. J. Leland, E. Fielding, R.S. Anderson, N. Brozovik, M.R. Reid & C. Duncan, 1996. *Bedrock incision, rock uplift and threshold hill slopes in the northwestern Himalaya.),* Nature 379, 505–510.

Burbank, D.W. & Anderson, R.S., 2001. *Tectonic Geomorphology.* Blackwell, Science, 274-278.

Burchfiel, B. C., Chen, Z., Hodges, K. V., Liu, Y., Royden, L. H., Deng, C. & Xu, J., 1992. *The South Tibetan detachment system, Himalayan orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt.* Geological Society of America Special Paper, 269, 41 pp.

Chopra R, Dhiman R.D. & Sharma P.K., 2005 *Morphometric analysis of sub-watersheds in Gurdaspur district, Punjab using remote sensing and GIS techniques.* Jour. Indian Soc. Rem Sens 33, 4, 531–539.

Dobhal D.P. & Kumar S, 1996. *Inventory of glacier basins in Himachal Himalaya, G*eological Society of India 48, 6,671-681

Dortch, J. M., Owen, L. A., Schoenbohm, L.M. & Caffee, M. W., 2011. *Catchment-wide erosion rates, glaciation, and topography of the central ladakh Range,* India, Journal of Himalayan Earth Sciences 44, 1, 14.

Fujita, K. & Ageta, Y., 2000. *Effect of summer accumulation on glacier mass balance on the Tibetan Plateau revealed by mass-balance model.* Journal of Glaciology, 46, 244-252.

Goswami, C., Mukhopadhyay, D. & Poddar, B. C., 2012. *Tectonic control on the drainage system in a piedmont region in tectonically active eastern Himalayas.* Front. Earth Sci. 6, 1, 29–38.

Goudie, A.S., 2004. *Tectonic activity indices, In Enclo - pedia of Geomorphology* Goudie, A.S.(Ed), Routledge, London, pp.1036-1037.

Grohmann, C.H., Riccomini, C., & Alves, F.M., 2007. *SRTM-based morphotectonic analysis of the Poc-os de Caldas Alkaline Massif, southeastern Brazil.* Computers & Geosciences, 33, 10–19.

Jordan, G., 2003. *Morphometric analysis and tectonic interpretation of digital terrain data: a case study.* Earth Surface Processes and Landforms, 28, 8, 807–822.

Julie, G., Berthier, E., & Yves, A., 2012. *Slight mass gain of Karakoram glaciers in the early twenty-first century.* Nature Geoscience, 5, 322.

Kale V. S. & Gupta, A., 2001. *Introduction to Geomorphology,* Orient Longman Limited, Calcutta, 274p.

Katsube, K & Takashi.O., 1999. *Altitudinal Changes in Slope Angle and Profile Curvature in the Japan Alps: A Hypothesis regarding Characteristic Slope Form,*Spring Meeting of Japanese Geomorphological Union, 1999. CSIS Discussion Paper 16, 18pp.

Keller, E.A. & Pinter, N., 1996. *Active tectonics: earthquakes, uplift and landforms.* Prentice Hall publisher, New Jersey, 338.

Malik, J. N. & Mohanty, C., 2007. *Active tectonic influence on the evolution of drainage and landscape: Geomorphic signatures from frontal and hinterland areas along the Northwestern Himalaya, India,* Journal of Asian Earth Sciences 29, 604–618.

Malik, J.N., Nakata. T., Philip.G., & Virdi, N.S., 2003. *Preliminary observations from a trench near Chandigarh, NW, Himalaya and their bearing on active faulting.* Current Science, 85, 12, 1793- 798.

Millar, W.S.S., 1997. *Identification of Mapped Ice-Margin Positions in Western New York from digital terrain-analysis and soil database*, Physical Geography. 25, 4, 347-359.

Mishra, N., 1988. *Hypsometric integral-A basis for determining the erosion status and priority number of ungauged watershed.* J. Soil & Water Cons. India, 32, 38-45.

Mohanty, C., Baral, D. J., & Malik, J.N., 2004. *Use of satellite data foe tectonic interpretataion, NW Himalaya,* Journal of the Indian Society of Remote Sensing, 32, 3, 241-247.

Molnar, P. & England, P., 1990. *Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg?* Nature, 346, 29 – 34.

Oguchi, T., Aoki, T., & Matsuta, N., 2003.

Identification of an active fault in the Japanese Alps from DEM-based hill shading. Computers & Geosciences, 29, 7, 885–891.

Owen, L. A., Benn, D. I., Derbyshire, E., Evans, D. J. A., Mitchell, W. A., Thompson, D., Richardson, S., Lloyd, M. & Holden, C., 1995. *The geomorphology and landscape evolution of the Lahul Himalaya,* Northern India. Zeitschriftfür Geomorphologie, 39, 145-174.

Owen, L.A., Finkel, R.C. & Caffee, M.W., 2002, *a note on the extent of glaciation throughout the Himalaya during the global Last Glacial Maximum*, Quaternary Science Reviews, 21, 147-157.

Philip, G., & Sah, M.P., 1999. *Geomorphic signatures for active tectonics in the Trans-Yamuna segment of the Western Doon valley, NW Himalaya.* International Journal of Applied Earth Observation and Geoinformation, 1, 1, 54-63.

Rabus, B., Eineder, M., Roth, R. & Bamler, R., 2003. *The shuttle radar topography mission a new class of digital elevation models acquired by space borne radar.*ISPRS Journal of Photogrammetry and Remote Sensing, 57,241 -262.

Rathore, B.P., Kulkarni, A. V. & Sherasia. N. K., 2009. *Understanding future changes in snow and glacier melt runoff due to global warming in Wangar Gad basin,* India, Current Science, 97, 7, 1077-1081.

Robl, J., Stuwe, K., Hergarten, S. & Evans, L., 2008. *Extension during continental convergence in the Eastern Alps: The influence of orogen-scale strike-slip faults,* Journal of Geology, 36, 12, 963-966.

Romshoo, S. A., Ahmad, S. & Rashid, I., 2012. *Geoinformatics for assessing the morphometric control on hydrological response at watershed scale in the Upper Indus Basin,* J. Earth Syst. Sci. 121, 3, 659–686.

Singh, S. & Singh M.C., 1997. *Morphomertric Analysis of Kanhar River Basin,* National Geographical Jour. of India, 43, 1, 31-43.

Szynkaruk, E., Graduno-Monroy, V.H., & Bocco, G., 2004. *Active fault systems and tectono-topographic configuration of the central Trans-Mexican Volcanic Belt.* Geomorphology, 61, 1–2, 111–126.

Thakur, V.C., 1995. *Geology of Dun valley, Gharwal Himalaya: Neotectonics and coeval deposition with fault- propagation folds.* Journal of Himalayan Geology, 6, 1-8.

Tobias, B., 2004. *Using ASTER and SRTM DEMS for Studying Glaciers and Rock glaciers in Northern Tien Shan Proceedings Part I of the Conference”* Theoretical and applied problems of geography on a boundary of centuries”, Almaty/Kazakhstani, 8-9 June 2004, p. 254-265.

Tobias, B., Kamp, U., & Jeffery, O., 2005. *Using ASTER and SRTM DEMs for studying geomorphology and glaciation in high mountain areas.*Millpress, Rotterdam, ISBN 90 5966 003 X.

Wang, Y. & Liao, M., 2005. *Analysis of the water volume, length, total area and inundated area of the Three Gorges Reservoir, China using the SRTM DEM data,* International Journal of Remote Sensing. 26, 18, 4001–4012.

Yang, X., Zhu, Z., Jaekel, D., Owen, L. A. & Han, J., 2002. *Late Quaternary palaeo-environmental change and landscape evolution along the Keriya River, Xingjiang, China: the relationship between high mountain glaciation and landscape evolution in foreland desert regions.* Quaternary International, 97-98, 155-166.

Zevenbergen, L.W. & Thorne, C.R., 1987. Quantitative analysis of land surface topography, Earth Surface Processes and Landforms, 12, 1, 47 – 56.

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