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Landform Transformation and Sustainable Habitability: A Himalayan Task

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Abstract: *Emergent climate change has accelerated the process of 'landform transformation', and increasing human interference, aided by technology-driven growth has led the way for the complex response of natural systems. Majority of the occupied surfaces remained metastable during the past few decades and are in the state of transformation to adapt to new sedimentation-erosion regimes in response to the altered weather conditions. Predicting the stability of these surfaces demands comprehensive modelling by integrating various parameters. Mountainous regions such as the Himalaya-Karakorum-Tibetan belt and the foothills are particularly vulnerable due to frequent fluctuations in sediment mass to slope ratios and relative base level changes intensified by climate change. The most crucial factors requiring parameterisation to develop quantitative dataset, must explain the conditions, such as altered pathways and conduits of sediment mass transfer under various energy conditions. These conditions, scales, magnitudes, and timings may anomalously vary during extreme events; and systematic studies in individual valley basins can address these uncertainties. A methodological approach for deglaciated mountain valleys, combining field observations with physical laws has been suggested here, encouraging new parameters for evaluating and estimating the dominating processes. This approach holds the potential for sustainable development. Interactions among these processes, their magnitudes, and scaling are discussed here for their application to sustainable development in such deglaciated mountain valleys.*

Keywords: Landform transformation, climate change, Himalaya.

Introduction

The exponential rise in human settlement and infrastructural activity in the narrow valley basins and mountainous slopes of the Himalayas, their foothills and plains have created competitive circumstances due to altered weather conditions. These mountainous regions are dominated by fragile sedimentary rock formations with high dip angles and changing structural trends that encourage heterogeneous and episodic mass-wasting processes. Rapid altitudinal changes in these mountains with rugged and fragile topography, leads to sharp margins of weather conditions within the complex monsoon system and westerly precipitation. Critical examination of the above conditions in individual valley basins under warmer climates and heavier precipitation is necessary to avoid future loss of life and damage to infrastructure.

Observing the surface (landforms) and inferring the nature of the processes is a classical approach in geomorphology and sedimentology. Recent improvements in documentation have led to a better understanding of the anthropogenic influence over such processes. The interaction of weathering, erosion, and sedimentation alters the landforms by secular processes accompanied by high-energy extreme events, and the latter are explained as disasters in the human dimension. Slow and high-energy processes affect human settlement and infrastructure at various time scales, facilitating metastable conditions till a threshold is reached (Schumm, 1979). Early humans generally responded to the slow geomorphic processes by migratory habits. In contrast, the increasing subsistence habits of modern humans demand the recognition of stable surfaces within the transient landform conditions.

Climate change has increased the frequency of landslides, cloud bursts, river damming, and glacial lake outburst floods (GLOFs) in terrains like the Himalayas (Sangode *et al*., 2022; Sangode *et al*., 2017a, b; Sangode *et al*., 2011a; Sangode & Bagati, 1996). Inadequate knowledge about the valley basins in terms of sediment availability, distribution and transport efficiency limits the generalisation of processes and their parameterisation. Identification of climate change-induced landform transformation requires a better understanding of the sedimentation and denudational processes in the ridge-valley setup of the Himalayas (e.g. deglaciated valleys of the Himalayas, Karakorum and Tibet). These mountains configure various valley systems with unidirectional exchange of mass and energy through youthful conduits. Presently, a greater mass is precariously accommodated amongst ridges, pediments, tributary valleys, and foothills, with the deglaciated valleys receiving meltwaters through the misfit river valleys. It is habitual for this terrain to receive snow precipitation and meltwater flows, but excessive precipitation and melting due to climate change have accelerated sediment mass transfer by altered processes.

Landform modifications with/without human intervention involves processes bracketed by low-magnitude rapid events below the threshold and high-energy events above the threshold. Schumm (1979) elaborated on intrinsic and extrinsic geomorphic thresholds to recognise their applicability in explaining sedimentologic and stratigraphic anomalies. The secular process, however, is first order non-linear but cyclic at higher order and can have exponentially increasing/decreasing trends. These processes can be identified as temporal units, such as fining/coarsening up cycles in sediment profiles, and may be spatially correlated within the basin. However, it is challenging to identify contemporary ‘landform transformation’ attributes and attempt their modelling in the context of the presence/absence of human settlements and infrastructure. Practicable implementation demands computational modelling through observation and parameterisation of the processes. These processes are more complex in mountainous regions like the Himalayas due to rapid base-level changes, structurally and lithologically controlled channel skewness, and changing gradients within short distances in tectonically influenced valley long-profiles.

The dynamic sediment-geomorphic threshold conditions include the seasonal/episodic processes. The colluvial and aeolian yields contribute additional sediment mass in the dry valleys of the Himalayas as significant inputs during episodic conditions. Identifying the spatio-temporal interferences to these processes in individual valley basins may help in better understanding of the metastable surfaces. Earlier, Sangode *et al*. (2022) attempted to identify the active-erosional and depositional fronts in the extended profiles of Chandra river (Lahual-Spiti Himalayan region) to recognise possible stable surfaces within the valley. A generalised methodological approach may be devised considering the varied geological factors of different river valleys. This article explores the possibility of such general conditions amongst the Himalayan ranges to develop a broad set of criteria for detailed study.

The UN sustainable development goals recognised the hydrological cycle as one of the most critical aspects. However, the abundance of freshwater from an efficient monsoon system and the availability of glacial melt water dilutes the significance of such goals in this region. On the other hand, understanding the natural disasters is essential for sustainable living in this area. Therefore, the article focuses on the sustainability of the mountain valleys by identifying stable/metastable surfaces. It addresses the role of planners, civil engineers, geologists, geographers, and social scientists in sustainable development. This study does not represent a classical geomorphological approach and is based on the author's observations as a geologist in several field visits carried out during the past three decades.

Setup of the Himalayan valleys

Himalayas are part of one of the longest and most prominent active mountain chains called the Alpine-Himalayan orogenic belt, which extends from Europe, through Asia to Southeast Asia, formed as a result of the collision of several plates and microplates prominent in the Indo-Eurasian collision zone. There are first-order similarities in the mechanism and style of folding (and faulting) throughout this belt. The orogenic evolution of this mountain chain together with the upliftment of the Tibetan plateau resulted in characteristic atmospheric circulation with its global impact. Laterally, the various sectors of this Alpine-Himalayan range also show a first-order similarity due to the maturity of compression along the converging plate boundaries. The climate-controlled weathering significantly normalised the tectonic aspects of the orogeny, leading to the characteristic geomorphic contours. Relatively fragile marine-to-non-marine lithologies dominate the Himalayas and the Indo-Burmese ranges. Laterally continuous topographic inversion, folding, and upliftment were followed by high rate of physical erosion during the Quaternary. Longitudinal parallelism of the wide ridges facilitated long glacial valleys. Multiple glacial-interglacial stages carved these valleys as easy conduits to long-distance mass transfer. The enormous volume of sediment available in the Bengal and Indus fans and the Indo-Gangetic plains depict the massive mass of sediment transferred from the Himalayas and Indo-Burma ranges during most of the Quaternary due to the competitive pace of climate and tectonic processes. Therefore, the sustainability of human settlements in these mountain regions depends on the recognition of metastable conditions.

The foothills of these mountains and the vast plains of Indus-Ganga-Brahmaputra extending in India, Pakistan, Nepal, and Bangladesh represent some of the most densely populated regions of the world. Heavy settlements are further creeping up into the higher topographic subdivisions of the Himalayas (Outer, Lesser and Higher-Trans Himalaya) to make it one of the most densely populated mountain ranges in the near future. Given the region's sensitivity to climate change and tectonics (seismicity), this population pressure demands an urgent concern for sustainable living.

In recent times the term ‘habitability’ has been used mostly for the planetary sciences, although it is equally important to consider the issue of habitability in mountainous regions like the Himalayas, demanding thorough geomorphic assessment. The matter of consideration lies with the availability of stable/ metastable surfaces for human settlement in one of the most dynamic mountain ranges of the world. The other criteria used for assessing habitability in this terrain consider availability of freshwater, land fertility etc., which is beyond the scope of this manuscript. Any detailed discussion on the meanings and synonymity of the terms habitability and sustainability is also not made in this text, rather they are used interchangeably in many places concerning the ‘stability of surfaces or the landforms’. Sustainability defines suitability of human habitation with minimal infrastructure but maximum safeguard from the natural disasters. In simple terms, the metastable surface is a place to live safely from any natural calamity for a relatively longer duration.

The modern topography of the Himalayan region manifests the Late Quaternary (Last Glacial to Holocene) climate and tectonic transition. The modern settlements are distributed on all geomorphic components from the mountain tops to the valley floor, that remained meta-stable during the past few decades. The misfit river valleys created during the past glacial stages are preferred spaces for human occupations with high population density. Due to the ease of water availability, the valley bases assume perceptibly stable surfaces over the eroded moraines, alluvial fans and paleo-landslide zones. Thus, from a geomorphologist’s point of view, most settlements are unsustainable and prone to erosion (toe-cutting), flooding, re-deposition, or any other natural process trying to achieve a stable gravitational base.

The Late Quaternary sediment cover and geomorphic surfaces can be broadly assigned to the last glacial-to-interglacial transition when the glacial valleys were transformed into post-glacial and fluvioglacial environments (Rawat *et al.*, 2012, 2021). Characterised by larger space for accommodating a fluvial system, these misfit valleys are veneered with a substantial mass of morainic sedimentation from the past glacial stages. Further, most of the flat valley floors represent channel incisions in response to the altered sediment-water ratio and/or upliftment. Longitudinally, these valleys show frequent undulations in their extended profiles with varying altitudes, widths, or skewness, creating drifts in sediment/water mass flows and overfilled to underfilled conditions within a few kilometres stretch (Fig. 1). Sangode *et al.* (2022) suggested that the relative basin fill conditions of valley floor may be assessed by the convergence of the denudational front and the depositional base level.

The longitudinal (trunk) valleys are significantly fed by the hanging valley tributaries approaching the base level with sharp breaks in gradient. The trunk valleys were carved through the past glacial stages, whereas the hanging valleys became most active during the post-glacial (interglacial) seasonal precipitation episodes as seen in the Holocene. Apart from seasonal inputs, these hanging valleys also provide episodic sediment inputs to the trunk valleys during extreme conditions, such as cloud bursts, impounding (damming) the trunk river, and an imminent disaster. Arrangement and spacing of these hanging valleys on opposite banks create critical conditions for damming. The adjacent fans may become susceptible to toe-cutting and can be raised as terraces. Forced meandering due to fan arrangement is common is such valleys. The unconsolidated nature of these fans and the steep valley gradient leads to excess sediment load being carried during extreme events. In normal conditions too, the sediment mass is mobilised to the nearby secondary depocenters (Fig. 1). The high energy episodes working on a peneplane surface formed according to the previous base level, mobilise the sediments and form a new raised base level of lower gradient, ready for the new depocenters to be formed proximal/distal to the previous one. The formation of obstacle-dunes, raised floodplains with grazing grounds, and shallow ponds are the signatures of metastable surfaces in these valley conditions. However, the stability of these surfaces can only be assessed after the entire long profile of the valleys are taken into consideration (Fig. 1).

The sloping valley walls produce colluvium, which are brought down by gravity and are reworked downstream during high energy episodes. Further, a large amount of mass is locked into the tributaries and hanging valleys, paleo-floodplains and terraces, and over the valley side walls as remnants of lateral moraines; ready to move during extreme events (Sangode *et al*. 2022; 2017a, b; 2011). The longer tributaries joining the trunk river too maintain their hanging valley, and secondary tributaries or gullies producing sedimentary output. The rising of base level is synchronous to lowering of denudational plane, has been observed and

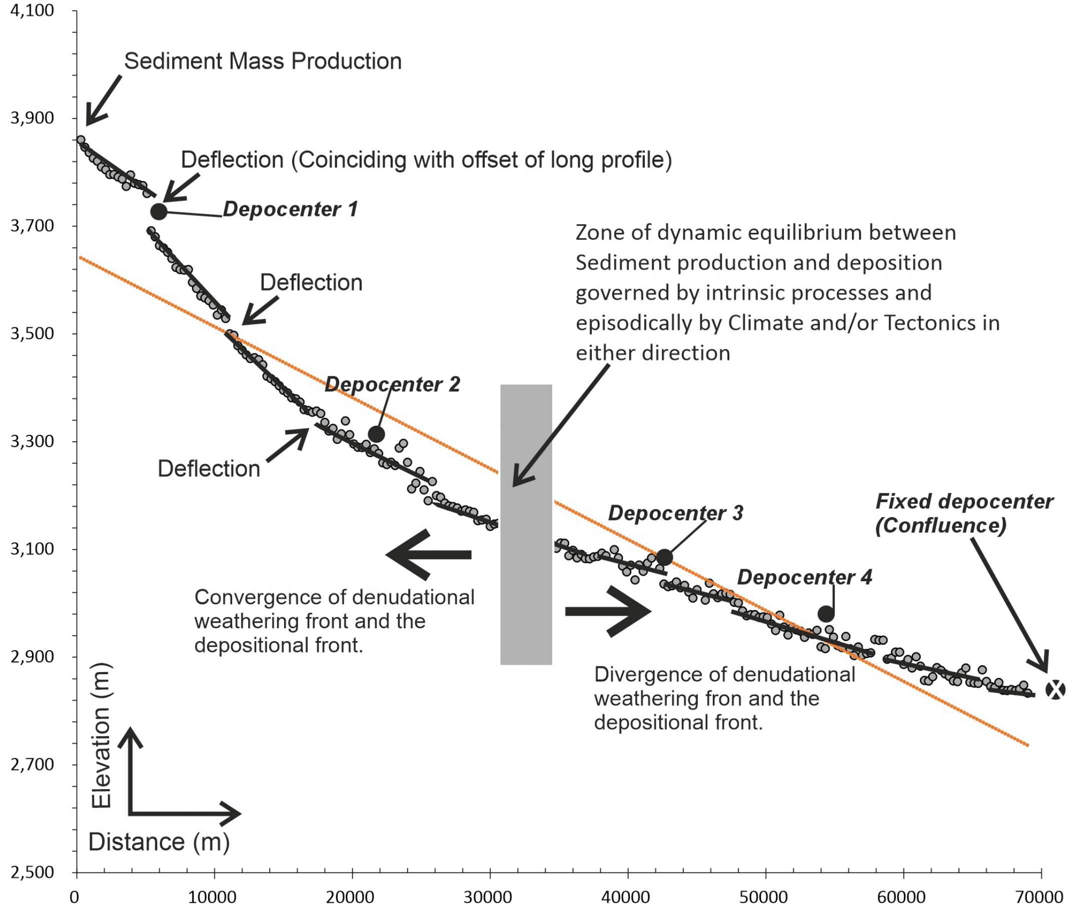

Figure 1. An example of a long profile from Chandra valley (modified after Sangode et al., 2022) depicting the episodic sediment transfer mechanism. The valley is in a state of landform transformation due to the transient climate of snow precipitation to seasonal rainfall triggered by climate change.

analysed by Sangode *et al*. (2022), as a typical pattern in the Higher and Trans-Himalayas. Change in base level also promotes sharper incisions on the floor of those valleys which are confined by nature. These characteristics, therefore, may be generalised and attributed to Himalayan-type valley basins.

The dynamic signatures of extreme conditions in the Himalayas are expected during the Late Pleistocene-Holocene glacial-interglacial transition and during the Late Holocene-to-Recent transition triggered by climate change and anthropogenic effects. Late Pleistocene events like river damming and lake outbursts are widely reported in the Himalayas, to have great significance for natural disasters in the region. These records are most significant for analysing sustainability and growth of settlements, and infrastructure development. Thus, there are numerous geomorphological parameters of a given valley, which are to be noted in field. Some of these parameters are mentioned below. Such parameters can be the foundations for advanced modelling in terms of investigation of the metastable surfaces.

Factors and parameters of landscape modification

The landscape modification in the Himalayan region may be attributed to the Quaternary glaciogenic modification of the pre-existing tectonic framework. Since tectonic processes differ in their frequency, magnitudes and time scale from that of climate change; the climatogenic processes may be considered intrinsic in this case. Variations in the response-time of climate change over geomorphic landscaping can result in several dynamic conditions. The irregularities in the longitudinal profile lead to activities like river damming and formation/breaching of lakes, landslides, and flash floods. Several previously reported paleolake records in the Himalayan region are linked to river damming (impoundment) during the late Pleistocene.

Based on the detailed case study from the Chandra Valley (Sangode *et al*., 2022; Rawat *et al*. 2015a, b) and widespread field observations by the author from Lahaul-Spiti, Leh valley, Pangong valley, and Kashmir basins; a model has been discussed here with possible implications for investigating stable and sustainable surfaces. The critical factors are summarised below, aided by figures 1 to 4.

Factor I: Annular shift in the valley profiles

Unlike the anticlinal/synclinal valleys or the lineament-controlled channels, many of these long glacial valleys are antecedent and depict greater undulations, maintaining the episodic nature of sediment transport creating secondary depocenters. Parametrisation of annular/axial shifts in the valley cross profiles may depict the dynamic response of the given channel.

Factor II: Estimation of entrapped sediment mass

If climate change permits higher precipitation, the larger seasonal yield of meltwater and precipitation will significantly accelerate the process of base-level upgradation and migration of secondary depocenters to create new relative base levels. It can re-set the sediment gradation process (clast size distribution), increasing roundness and hence the transport efficiency with peneplanation of the secondary depocenters and the remnant morainic material (Fig. 3). The entrapped sediment mass, therefore, needs to be estimated for their transport efficiency and redeposition.

Factor III: Tributary to trunk relationship

The tributary-to-trunk acute angle relationships recharge the trunk channel, while the obtuse angle promotes damming-like condition. Further, the difference in gradient of the tributary and trunk channels would alter the nature of release of sediment to the trunk river. These can be treated as angular or gradient breaks to be considered for the parametrisation.

Factor IV: Catchment to basin configuration

The proportionately large area of the catchment, its heterogeneity relative to the depositional area (valley floor), and narrow high-gradient valleys (first- or second-order streams) are some of the most precarious conditions in the Himalayas. This is one of the most important factors, as the valley responds to extreme conditions such as cloud bursts (Sangode *et al*., 2017a), and even the metastable surfaces need to be re-assessed. It demands derivatives to estimate the effect of the catchment area on the stressed channel area and the relatively open basin floor area.

Factor V: The channel fill dynamics and base level upgradation

The characteristics of mountain rivers are the confined valley floor width, wide interfluve area, and significant input from the side walls and pediments. Narrow and deeply incised channels with fixed thalwegs create lock-in conditions for the incising stream channel, making frequent attempts of forced avulsion and forming parallel and anastomosing streams. The incision of these trunk valleys is not controlled by bedrock configuration, but the self-incision of the valley fill (filled during the past glacial events). These conditions accelerate base level rise. The grain sizes are dominated by larger

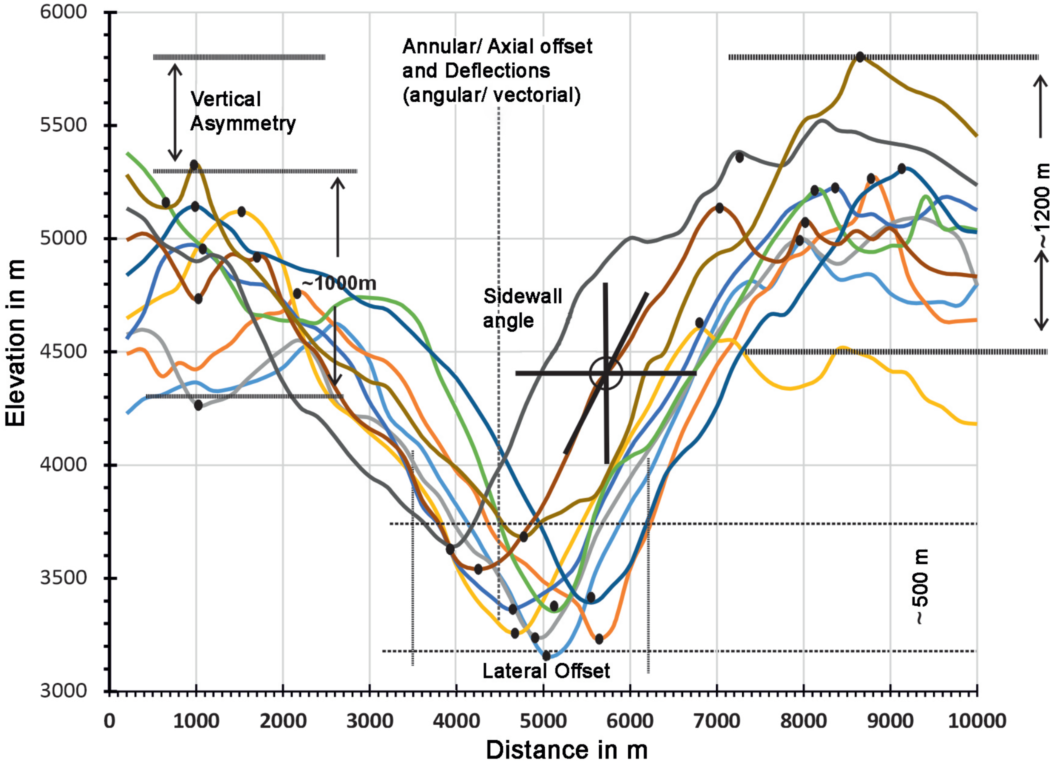

Figure 2. Annular shifts in the valley cross profiles measured by the offset of the valley long axis, lateral offsets of thalweg downstream, and right and left valley wall denudational offset. The cross profiles shown are from one of the segments of Chandra river depicting a deflection of >500 m (Sangode et al., 2022).

clasts and boulders, and the steep sided valley walls and tributaries feed many different clast grades dominated by angular clasts due to shear-dominant orogenic regimes. The increasing meltwater runoff creates dynamic sediment transport conditions, even without extreme events. Added to this are the pediments (colluvial/scree fans) available to move large mass of dry colluvium during the higher flow regimes. Forced meandering of the channel due to encroaching colluvial fans is also common. To explain the unique morphodynamic conditions of the Himalayan valleys, the existing parameters influencing sediment yield, should be considered together with the conditions influencing stream power and transport capacity of the streams. The temporal resolution and magnitude of error of the conventional parameters is challenging to understand the sustainability of valley forms for future developments under a particular climate change regime.

The studies conducted by Sangode *et al.* (2022; 2017a, b; 2011a, b) and Rawat *et al.* (2015a, b; 2012) are evaluated with additional field observations to attempt generalised models and suggest more parameters suitable for the Himalayan basins. However, these models are primordial and generalised, and more observation-based data from additional valleys can lead to better computational derivatives and empirical relations for their use in predictive modelling.

Factor VI: The geological setup

The geological setup mainly governs the deflections (offsets) and must be parametrised to characterise the given valley for various inferences. The valley deflection (offset) can be measured as vector-based parameters (direction and magnitude) along with regional structural and tectonic data to determine their cause and attitudes. Tectonic uplift can lead to rapid change in the channel gradient even if the uplift is inactive due to differential response of lithologies to abrasion. Figure 2 notes the variation in profile elevations and other offsets as accounted below.

1. Vertical offset of side valleys (left and right) = V_S
2. Lateral shifts in the valley floor axis = V_L
3. Vertical offset of the annular/axial hinge line of the valley bottom = V_A
4. Valley angle deviation for left and right walls = D_L and D_R

The Vs is influenced by tectonics, and without any extrinsic factor (climate in this case), the Vs should be zero. Advanced computation modelling and refinements of such parameters are needed. The cross-profile elevations can be plotted considering an average extended profile to find the anomalies leading to secondary depocenters. The displacements (due to deflection) of the profiles create the scope for sediment entrapment.

Other influencing factors include lithology, which is represented by composition and attitude of the underlying beds. Rock strength is an expression of the composition, the erodibility pattern of the beds. The dip-strike orientation concerns valley orientation and the intercept of active faults leads to local upliftment in the valley. Many other geological factors may be kept aside at the scale being examined for sustainability. However, the region's seismicity is of utmost importance as it can trigger landslides and avalanches, influencing the valley sediment regime and the stability of precariously balanced profiles.

The longitudinal profile of Chandra valley (Fig. 1), with its discrete nature, aided by field observations, depicts signatures of secondary depocenters created at those deflection points. A transitional zone can be identified as an equilibrium zone for sediment production and deposition. It is crucial to determine the field signatures depicting the migration of this zone up/ down, and its relation to profile gradient, and other factors mentioned above. These factors depend upon tectonic reactivation and climate change.

Parametrisation of the landform transformation and stability of surfaces

The relative base level described here indicates an average plane of reference for the seasonally averaged water level surface. The T_0 is the active terrace surface, and the equilibrium level where the net erosion equals deposition in the valley. Therefore, the base level mentioned here deviates from the classical definition of Davis (1902) or Chorley *et al*. (1964). This base level is a dynamic surface matching the gradient of the long profile. It tends to achieve a gravitationally stable relative base level, as marked by the plane of relative base level (B_L). The relative B_L is dynamic, and it can be B_{L1}……....B_{Ln} till it reaches the level where sediment transport is nil (B_L0) — a perfectly stable surface. When the basin is overfilled with sediment it marks the onset of the process of inversion of relief. Previously, Sangode *et al*. (2022) suggested the divergence and convergence of the denudational versus depositional fronts to identify the stable/ meta-stable surfaces. These concepts can be realistic if such parameters are based on more detailed field and satellite data. The signatures of these parameters at any given point should be checked through ground truthing.

The precariously accommodated sediment mass amongst narrow ridges, pediments, tributary valleys, and foothills within the deglaciated valleys is ready to be mobilised during heavy precipitation or extreme events. The terrain is being transformed by precipitation in the form of snow to rainfall, and the increasing volume of meltwater further need to be examined for estimating denudation rates, sedimentation rates, and rates of sediment transfer. Taking examples from Chandra and Leh valleys in the Higher

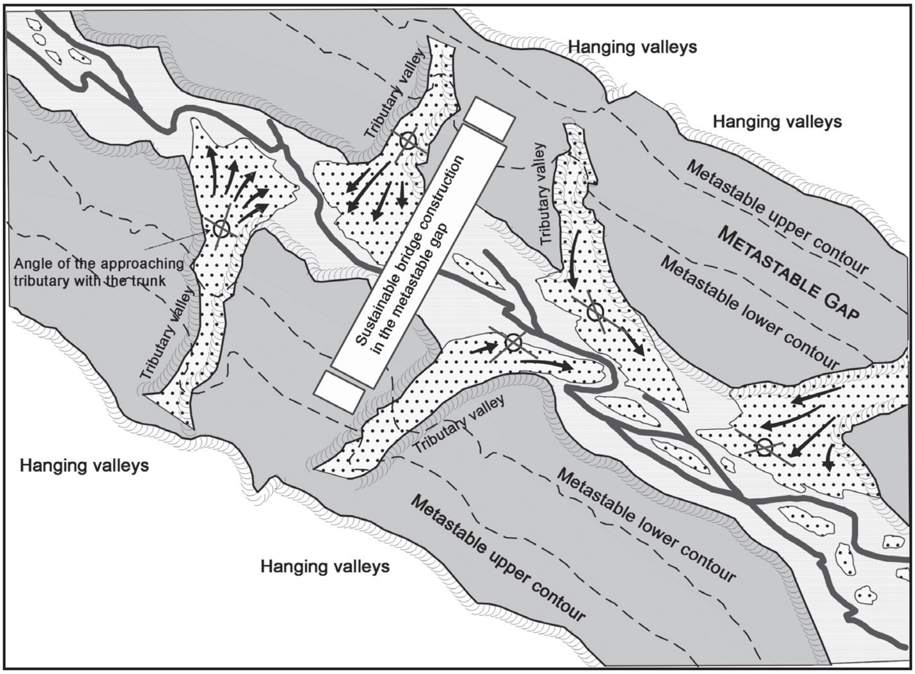

Figure 3. A sketch showing the angular relationship among the tributary and trunk system, depicting the significance of factors described in the text. There can be infinite combinations of these angles and the gradients of their plane of base level.

and Trans Himalayas, the interaction of various surfaces concerning an imaginary gravitational surface of peneplanation (B_L0?) may be assumed for finding stable surfaces in relation to human settlements. The spasmodically governed depocenter dynamics against the episodic mass transfer need to be estimated, and the scales and frequency of these processes should be validated by ground truthing. Floodplain divergences and constrictions (examples from Chandra and Leh valleys) and interfingering colluvial fans encroaching the trunk river increase the susceptibility to river damming. Whereas the base level articulations and depocenter dynamics reflect the course of relative B_L surfaces on the valley floor. Tectonics (thrust-related uplift or strike-slip-related valley offsets) is considered central in estimating the anomalies amongst the rate of valley fills and magnitude of incision. The ridge-to-valley slope angles and precarious sediment masses (possibly the remnant lateral moraines) can be estimated along with the colluvium geometry, mass, and mobilisation. New first-order streams and empowerment of the existing minor streams are observed in the Chandra valley as part of the reactivation process.

The first-order parameters may begin with the valley evacuation factor (V_E), considering that most of the valleys in these mountains have been deglaciated during the Holocene. However, these valleys evolved through multiple glacial stages, the signatures of which can be traced and reconstructed from the careful observation of long and cross profiles apart from the field and the remnant sediment units. The evacuation, therefore, is episodic through stages and needs to be estimated separately and collectively by the parameters V_E1 and V_E2…., incision and uplift (Fig. 2–4). The available sediment mass can be calculated from the field by reconstruction and extrapolation of remnant sedimentary units, shallow subsurface geophysical surveys, and satellite mapping. The relative base level (B_L) drops through glacial stages can be derived as B_L1, B_L2… (Fig. 4). The figure also tries to emphasise upon deriving the following factors; i) Profile asymmetry factor (A_F) related to the valley cross profiles asymmetry with reference to left and right banks; ii) Degree of deflection of the long profile (D_F) considering an idealised line for the long profile, the offsets in the profile in terms of lateral and vertical offsets (along x- and y- axis and overall vectorial shift) mainly governed by tectonics and lithology; iii) Valley convergence/divergence angles (V_A): widening and opening of the profile downstream can affect the sediment transport regime. The convergence/divergence can be expressed by positive and negative angles concerning the lines parallel to an idealised long profile with no convergence and divergence; iv) Metastable gap (M_G) is the difference between the denudational front and the depositional front (previously explained in Sangode *et al.* 2022) and derivatives of M_G as a function of long profile variability including the gradient. The metastable gap is a valuable parameter towards the investigation of stable surfaces, the contours of which will depend upon several factors highlighted above; v) Valley evacuation factor (V_E) to be derived by taking into account the cross-sectional area of valley to cross-section area of sediment mass (to be reconstructed from the remnant profiles available in the given cross section); and there can be V_E1, V_E2... For different glacial stages experienced by the valley in the past.

The applicability and success of such a study need an individualistic valley basin approach. With this broad setup of the Himalayan valleys, it is necessary to establish a rational computational relationship between various parameters, such as the sediment mass available and the base level and the predictive changes in the base level during extreme conditions. Characterising the nature, mass, magnitude, and the base level changes due to flash floods triggered by various causes such as cloud bursts, river damming, glacial serge, earthquakes, snow avalanches, etc., should be undertaken. This will help in prima facie identification of the stable surfaces before studying the stability of the individual surfaces in detail. The Himalayan valleys show extreme morphological heterogeneity due to geological factors and should be examined individually. The examples produced here are of specific valleys, and the inferences drawn are more towards setting up the approach rather than generalising the effects.

Future perspectives

Sustainable living in the mountain valleys demands stability of the surfaces for settlement. This issue is directly concerned with 'landform transformation' that is being studied in classical geomorphology and sedimentology. The mountain valleys are preferred locations of settlement and the issue of landform transformation amongst the valleys deals with the process and mechanism of sediment transport and deposition apart from many other factors, some of which are described in the preceding text. Developing sustainable settlements in mountain valleys, requires models for predicting ultimate sediment mass to be received at any given point downstream, along with flood levels with experiments on different intensities of extreme events, and the possible surfaces that will remain unaffected during such instances. This demands sedimentological and geomorphological acumen. The warming climate in the Himalayas is holistically changing the thermal contours that, over the regional altitudinal scales, is advancing/ retreating the entire 'ecosystem contours'

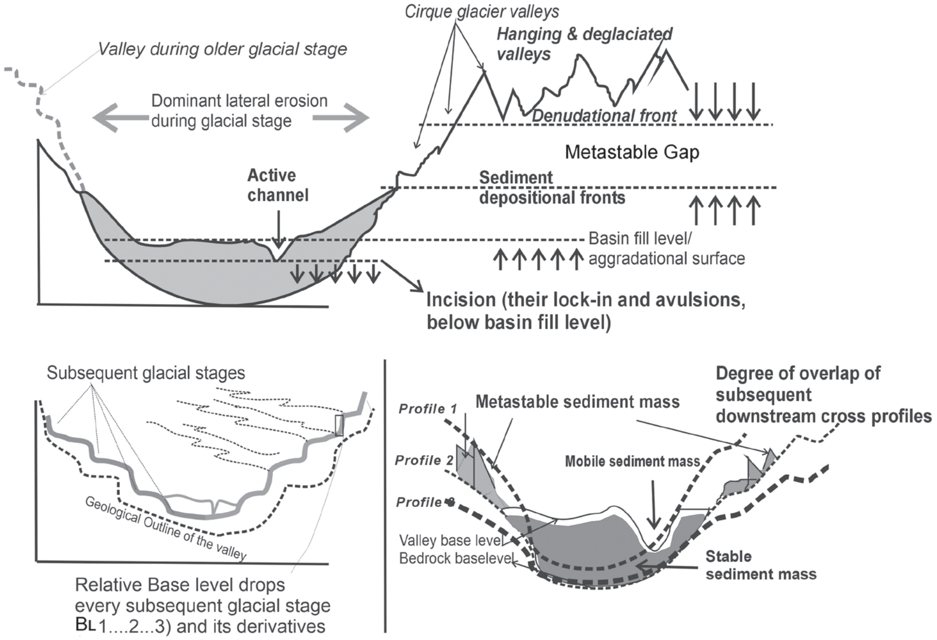

Figure 4. Models depicting the basis of various parameters and factors suggested to evaluate a mountain valley system in the Himalaya. The details of the parameters and the concept are given in the text.

(including the viral ecology). The Himalayas being most sensitive to climate change, the upward shift of these thermal and ecosystem contours needs to be traced to monitor and estimate glacial retreat through the migration of snouts. Therefore, inputs from physicists, bio-scientists, and ecologists are necessary to find sustainable options.

This paper focusses on stability of the surface, and the terms 'stable' or 'metastable' described here are temporal and relative in the context of their sustainability in the Himalayas. Determining these temporal limits and devising parameters based on geomorphic observations is crucial. The stable surfaces of settlements are to be interconnected by roads. The road network in the Himalaya never takes the shortest distance but through pathways that has greater probability to intercept with the natural calamities like landslide, avalanches, floods etc. However, sustainability can be enhanced by considering the option of bridges within the metastable gap contours. This will facilitate the shortest connectivity and reduce chances of damage. This is an example of the applicability of this work in developing sustainable options in the Himalayan terrain.

Habitability in the Himalayas, therefore, needs to be thought of in terms of relative and time-dependent stability. Likewise, subsistence and resistance are relative and interchangeable with reference to these metastable surfaces. To exemplify a paleo-landslide can produce stability of the surface above the base level in the Himalaya. Geomorphological investigation coupled with sedimentology can be pivotal in solving these conundrums and help in decision-making.

Geologically, none of the surfaces in the Himalayas are stable enough to remain horizontal with subaerial exposure for a long duration, and relocation is the key. Since the paper is conceptual in its approach, each parameter suggested above needs to be testified and defined by a collection of information from the given valley and data-based modelling. The description of individual parameters displayed amongst all the figures (1 to 4) is also limited and represent only broad experiential observations. Developing a rational derivative and computation for these parameters is, therefore, a necessity.

Advanced modelling

Modelling is beyond any specialisation and the expertise requires a team effort of geographers, geomorphologists, geologists, civil engineers, architects and planners. In this, geomorphology plays the most vital role, infusing all these branches, having all the components of fundamental, classical and advanced geomorphology.

The valley system ultimately represents the exchange of mass and energy and its dispersal, which can be expressed using the concept of entropy in thermodynamics. Considering the valley as a unit cell or an infinite assemblage of unit cells, the entropy expresses the dispersal of matter under disturbed energy conditions. The valley considers different components independently, whereas the concept of entropy allows us to evaluate the exchange of matter and energy as one integrated system. This systems approach has the advantage of being used for advanced modelling. The output of one sub-system is input to another thermodynamically connected system. The exchange can be estimated by considering an energy-mass sub-system-I, having higher entropy than sub-system-II, and the subsequent subsystems. The energy of sub-system II is generally less than sub-system I, and at a given point of time, they are operating simultaneously. The critical time is reached when the energy and mass of sub-system II dominate sub-system I. Further, the latter diminishes at the time of landform transformation, where the sub-system II exceeds the sub-system I, having no energy and mass to move and the entropy will be expressed as zero. Whereas the sub-system II interacts with the sub-system III in the same manner as it did with the sub-system I. The sub-systems I, II, III….n stops operating, when no significant energy transfer/ dispersal occurs, the surface become stable, and the basin tends to proceeds towards inversion.

Since entropy is a function of temperature, the glacial-to-interglacial transition presents an ideal experiment for increasing entropy. In contrast, the transition from interglacial-to-glacial needs to be tested, and several details need to be assessed for a natural system like a mountain valley. Considering the valley as a closed system of an imaginary rectangular block along the extended profile, there is an exchange of mass and energy governed by fundamental forces like gravity, the kinetic energy driving the forces of fluid dynamics through water and glaciers; the resultant of all the forces leads to transportation. This requires a detailed understanding of the factors and parameters as described in the text. The entropy accelerates/ decelerates due to disequilibrium/ equilibrium amongst these various components doing work that can be expressed in the sedimentological and geomorphological analysis. Therefore, advanced modelling must consider all the physical and chemical processes and laws. However, we need to be careful about the direct application of these laws that are idealised in laboratory conditions, and their applications in natural systems may be complex. At the same time, the integration of natural signatures would make them extremely useful for advanced modelling and such an approach is warranted in the advancement of our understanding and development of application-based approach in geomorphology.

The discovery of the buried in-situ archaeological records of settlement depicts that the surface was stable for that specific time period. The buried records may also indicate the aggradation of the base level or the basin fill conditions by intrinsic drops in the base level due to lithification and compaction (climate and tectonics may be considered as extrinsic conditions in this context). The relative dating of the archaeological settlements can depict the duration of meta-stable conditions in the given valley location.

A geomorphologist must identify whether new first-order streams and lakes emerge due to enhanced melting during climate change and whether the glacial melt-lines drawn from the snout contours retreat at a different scale from the that of the thermal contours. A vast range of data will help a geomorphologist to develop models by correlating the thermal contours with the glacial snout-position data; to assess how the thermal contours affect sediment production and transfer over sloping surfaces or to estimate the number and dimension of lakes and streams that can emerge from snow melt and damming. This data should be ready for developing an interdisciplinary approach by integrating the ecological changes parallel to the thermal changes. Which species of plant, vector, and microorganism will advance the most? Future geomorphologists has great scope as well as challenges in studying landform transformation due to climate change, and finding stable surfaces for human settlement and infrastructure and highlighting its latitudinal and multidisciplinary aspects.

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