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Hydro-geomorphic characterisation and erosion risk assessment of sub-watersheds by hypsometric analysis using geo-spatial techniques

Amrita Kar[1] and Sandipan Chakraborty[2]

[1]Department of GIS Analyst, New Town, Kolkata, India
[2]Department of Geology, WBES, Kolkata, India

ABSTRACT

Various components of topographic evolution, such as hypsometric, clinometric, and altimetric analysis, are highly effective for hydro-geomorphic and geomorphometric characterization as well as Erosion Risk Assessment (ERA) of watersheds, further contributing to sustainable watershed development and management from micro to macro levels. Overall development plans and present status of development are mostly dependent on geomorphic, topographic, morphometric and finally hypsometric analysis of the present watershed, which has distinct geo-litho- structural prints of ancient terrain and at the same time neo-tectonic episodes like tertiary deposits as well. The present study aims to determine the hydro-geomorphic status of the sub-watersheds at the same spatial level to infer the evolutionary stages of geomorphic development, thereby assessing the status of watershed resources. Geo-morphometric observation and analysis are accomplished and executed at the sub-watershed level to appreciate and comprehend the underlying geo-hydrological and geomorphic processes and to extract the inferences from the considered watershed parameters. For this purpose, Hypsometric as well as statistical analysis are taken into consideration to determine the hydro-geomorphic status of the sub watersheds to carried out at the same spatial level to infer the evolutionary stages of geomorphic evolution, which can help to determine the status of watershed resources. Moreover, derived hypsometric Integral (HI) quantifies as well as qualifies the geomorphic and erosional status of development in the sub-watershed level of Upper Kasai watershed. Inferences from the result, analysis and interpretation offer the most effective and crucial points for micro- level development and planning to economists, land planners, decision makers and finally to the geo-scientists in relation to human-watershed interface.

KEY WORDS

Hypsometric analysis; Geo-morphometry; Hypsometric integral; Erosion risk assessment; Human-watershed interface

ARTICLE HISTORY

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Introduction

Hypsometric analysis and interpretation of watersheds across the globe have long served as one of the most effective approaches for evaluation, prioritization, and erosion risk assessment down to the micro-watershed level [1,2]. The term Hydro-geomorphology is a complex as well as a comprehensive term in this respect and broadly treated as a scientific correlation and association of land and water bodies relating to geographical, geological, geo-hydrological, geo-morphometric, geomorphological and anthropogenic transformation of the land environment in response to the variation as well as the fluctuation of water flow on the land. Hydro-geomorphic parameters are the significant factors to determine the rank of a watershed, which are primarily bracketed into morphological, hypsometric, and hydrological classes and subsequently qualify the structure, function, and geomorphic activities of the watershed. Hypsometric curve (HC) analysis for numerous drainage basins [3] is a significant indicator of differential watershed status. The shape of the various HC is an indicator of watershed evolution , whereas the values of HI are closely associated with the degree of dissociation in relation to the balance of erosive and tectonic forces [4-6]. Moreover, the values of HI are significant geomorphological as well as watershed health indicators for distinguishing the evolutionary stages of watershed development. Hypsometric analysis, in relation to the watershed geomorphology, is treated as a crucial tool for comprehending the hydro-geomorphic characteristics as well as the estimation of erosion and geomorphic stages of evolution [7,8]. These forms of analyses and interpretation provide descriptive as well as quantitative perception and intuition into the shape, topography, drainage network, and status of landform evolution, which in turn control and regulate the hydrological and geomorphic processes in the watershed [9]. Moreover, by studying the nature of HI, we can assess the relative erosion risk in any watershed because it highlights the physio-ecological status of the watershed, which can help to prioritize the compartments for development, conservation and management. Hydro-geomorphic parameters involve the topographical, morphological and hydrological variables that define the watershed evolution status in an integrated manner [10]. The major morphological components include linear, aerial and relief and hypsometric parameters, which are able to explain the morphometry, geometry, drainage network, elevation status and ruggedness and roughness status of the watershed. Among them, hydrological parameters and

***Correspondence:** Dr. Sandipan Chakraborty, Department of Geology, WBES, Kolkata, India, e-mail: myself.sc58@gmail.com

hypsometric parameters are most significant in estimating the hydrogeomorphic and erosion risk status of the watershed [11]. The significant hypsometric parameters are the shape of the HC and HI, evaluating the distribution of topographic elevation and stages of watershed evolution [12,13]. Apart from hypsometric parameters, hydrological parameters like Runoff coefficient (C), Lag time (Lg), Time of Concentration (CT), Peak Discharge (Qp) and base Flow Index (Bf) are most commendable indicators with the interaction of water flow in the watershed with the prevailing geomorphic characteristics of the area [14,15]. Not only that, several geomorphic indices, LULC parameters, and sediment yield and erosion-related parameters also have a significant impact on the hydro-geomorphic status of the watershed [16].

Study Area

The present study region (The Upper Kasai Watershed) in the Purulia district is located on the eastern slope of the Chhotanagpur plateau and forms the southwestern part of West Bengal and a very small pocket of Jharkhand [17]. The studied watershed is constituted by 16 micro-watersheds covering 14 C.D. blocks of Purulia district (Figure 1). For a better understanding, the area has been divided into several sub-watersheds for getting their individual status in relation to development and management [18,19]. The area is intersected by the tributaries of the main river Kasai, and all those rivers are flowing from west to east, following the regional slope. Apart from Kasai, Saharjore, Bandhu, Kumari, Nangsai, Hanumata N, Jore, Chaka, Totko, Patloi, etc., are all the tributaries of Kasai. This part of the Purulia district, constituting the present watershed comprising ancient terrain with old metamorphic rocks and in the lower section of the studied part have neo-tectonic impression and recent deposits [20,21]. The present watershed (Upper part of the Kasai River basin) is very much significant in relation to physical, geomorphic, tectono-structural, pedo-geomorphological, climatic, availability of water, etc., and offers distinctive characteristics in relation to surrounding areas [22]. A considerable percentage of areas under study, like Sahar jore, upper Bandu, Jam, Jamuna, etc., are inaccessible, and most of the areas are nearly uninhabited and densely covered by forest. So, for optimal resource utilization, assessment of water resource potential, nature of anthropogenic intervention, development and sustainable management plan are to be organized properly [23,24].

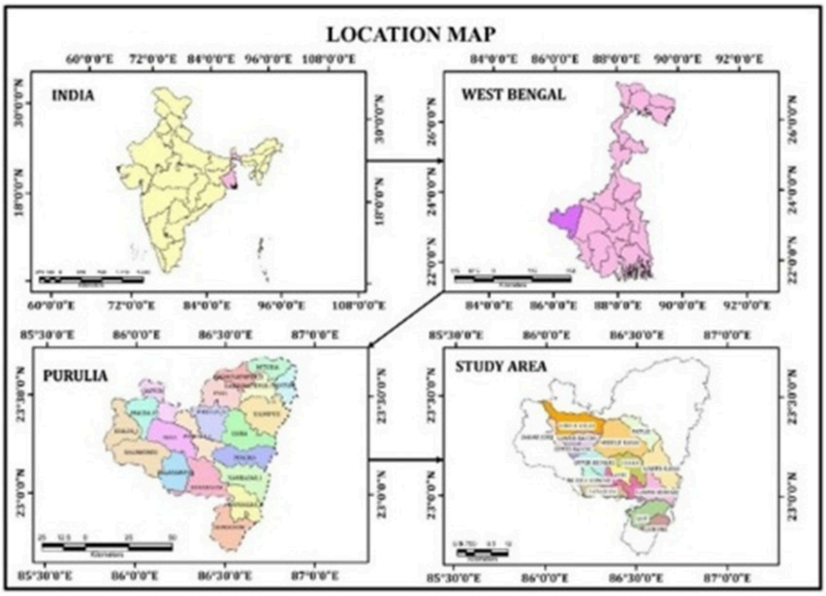

Figure 1. Location of the study area.

Objectives, database and methods of investigation

The primary objective of the present study is to characterize the hydro-geomorphic status of the upper Kasai watershed with a view to assessing the erosion risk in the watershed. For this purpose, geomorphic, hydrologic, morphometric and hypsometric indices are to be taken into consideration to assign the erosion risk assessment of the watershed [25]. Apart from SOI Topographical maps of 1:50,000 and 1:25000, various multi- temporal satellite images are collected to fulfil the present form of study. To draw and analyze the hypsometry of Upper Kasai Watershed, ASTER DEM was downloaded with 30m spatial resolution (https://search.earthdata.nasa.gov/) and processed the same on modern GIS environment (Arc GIS 10.6 software) for the demarcation of watershed and sub-watershed boundaries. For the rectification of the watershed boundaries, Survey of India 1:50000 Topographical Maps were used [26,27]. Further DEM of each sub- watershed extracted and reclassified into multiple relief zones using GIS technology. Spatial Analyst Tools from Arc GIS 10.6 software were used to obtain the area, minimum altitude, maximum altitude, and relative altitude of each relief zone of subwatersheds for the analysis of hypsometric status [28].

Generation of Hypsometric Curve (HC) and Extraction of Hypsometric Integral (HI)

Its theoretical interpretation and relevance to the present study

To find out the geomorphic status through hydro-geomorphic analysis, shape and orientation of the HC and values of HI are critical tools and play a vital role in explaining the evolution of watershed geomorphology, as it

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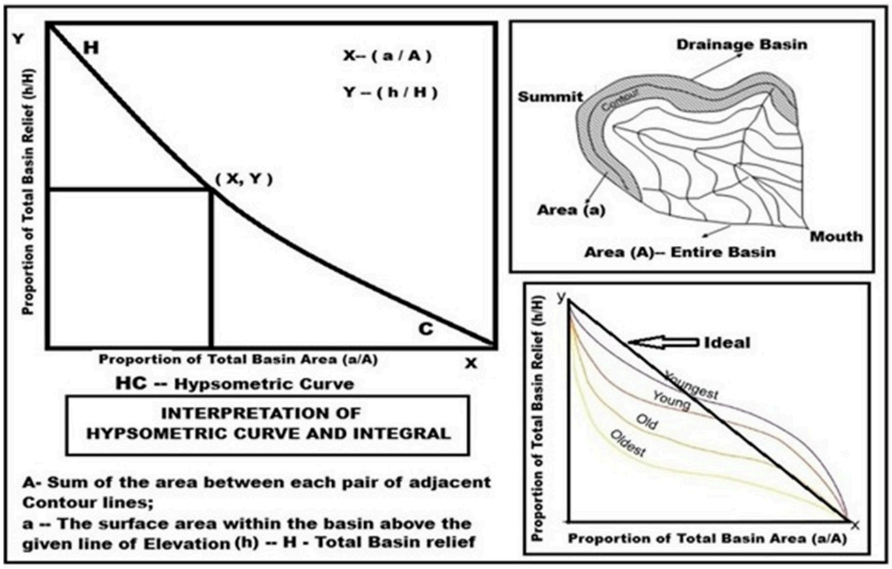
helps to quantify and visualize the relationship between the elevation of a watershed unit and the distribution of landform units within the watershed. The major objective of the hypsometric derivation is to extract a relationship between the abscissa (x) and ordinate (y) where, cross cross-sectional area and the elevation of the watershed are depicted in dimensionless form [29,30]. The resultant curve has been generated by plotting the results of relative elevation (H/h) in the ordinate against the (A/a), the relative area in the abscissa [31]. After getting the shape of the curve on the coordinate, the HI are to be calculated. HI is a deduced area under the HC, which is equivalent to the ratio of the area below the curve to the ratio of the area of the entire square and expressed in percentages [32]. Significant roles are played by HC analysis in the evolution of watershed geomorphology. It helps to define – a) the topographic diversity of the watershed/sub-watersheds concerned; b) the nature and characteristics of watershed development and evolution; c) to assess and estimate the erosion-accretion processes within the watershed which have major impact on the evolution of watershed; d) the inter-link to hydrological processes which have major implications on the hydro-geomorphic characteristics of the watersheds; e) the mode of classification of landform and subsequent analysis that may evaluate the morphological characteristics of the respective watershed; f) the land cover- land use status and environmental planning of the watershed (Figure 2) [33,34].



(Redrawn after Sinha Roy 2002; Strahler 1964, Willgoose and Hancock 1998).

Figure 2. Analysis and interpretation of the HC and the HI.

The HI, a dimensionless index number and calculated with the help of the aerial distribution of land with respect to elevation. It is also a significant geo-morphometric technique that is extracted to highlight the stages of geomorphic evolution, especially in terms of erosion, sedimentation, and the temporal status of landforms within a watershed or a basin. It is extracted from the following principle [35]:

$$HI = \frac{H_{(mean)} - H_{(minimum)}}{H_{(Maximum)} - H_{(minimum)}}$$

With the quantification of horizontal and vertical distribution of land, the values of HI can help the geomorphologists to enlighten the erosional status, processes of sedimentation and landscape evolution in relation to time [36]. The HI indices are also important quantitative markers to track the transformation of land from initial to decaying stages. It also offers a deep perception into the correlation and association among the tectonic, structural, climatic and exogenetic forces in the evolution of surface configuration from initial to senile stages [37,38]. Hence, the HI indices in the studied sub-watersheds are treated as an essential parameter in explaining the watershed status, history of landscape, as well as environmental planning and management. Values of HI generally range between 0.15 and 0.85, and typically cluster between 0.4 and 0.6. The differential values of HI signify the following distinctive stages of landform evolution (Table 1) [39].

Table 1. Analysis and interpretation of indices of HI.

Stages of landform evolution	Values of HI
Early YouthStage	> 0.60
Youth stage	(0.60 ≥ 0.50)
Early maturestage	(0.50 ≥ 0.40)
Mature (Late) stage	(0.40 ≥ 0.30)
Old stage	(0.30 ≥ 0.20)
Senile (Ageing and Worn) stage	(HI ≤ 0.20

The components of geology and geomorphology, geo-litho-structural geomorphology in association with the landform development of the studied region, are directly influencing the shape of the HC, determining the elevation distribution, erosion rate, relief and topography of the prevailing landscape, serving as an effective tool for detecting the geo-chronological status of the watershed [40]. The differential variation of the shape of the HC reflects the correlation and association among the Litho- tectono-structural activities, degradation and aggradation processes. With the help of interpretation and analysis of these factors, earth scientists can interpret the chronological dynamics of the landscape evolution in the region [41].

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Table 2. Impact of HC and HI in relation to the processes of landscape evolution.

Geomorphic Stage	HI Value	Hypsometric Curve	Landscape Features	Geomorphic Processes
Youthful Stage	Low (0.0–0.25)	Steep gradient;high elevation areas dominate	Steep slopes,ridges, and active incision	Active erosion,river incision, tectonic uplift
Mature Stage	Low (0.0–0.25)	Concave shape, balanced elevation distribution	Rounded hills, moderate valleys, floodplains	Erosion, sediment transport, deposition
Old Stage	High (0.50–1.0)	Flattened curve; low elevation areas dominate	Plains, broad valleys, floodplains, terraces	Extensive erosion, sediment deposition and levelled terrain

For the geomorphic characterization and flood risk assessment of the present watershed, the hypsometric analysis offers a deep insight into the stages of landscape evolution, processes of degradation and the nature of the watershed through the quantification of horizontal distance and elevation of a landscape. The following assessment can be estimated for the same:

- The differential shape of the HC (showing the proportion of total area above a given elevation) helps to identify the maturity stages of the watersheds. It can be designed as Convex, Straight, Concave, Convexo-concave and Concavo-convex, which are the indices of youth, mature and old stages of landscape evolution. Convexo-concave and concavo-convex reflect the compound stages of evolution, indicating early maturity and late maturity with neo-tectonic events, e.g., the tectonic movement, strong lithological intervention, differential erosion, etc., which are also the strong markers to interpret the geomorphic history of the watershed [42,43].
- The quantitative information derived from the HC, stated as HI, a non-dimensional value, indicates the degree of dissection, noted as low, moderate and high (Table 2), denoting youth, maturity and old stages of landscape evolution, predicting the delivery of sediment load to downstream areas and the impact on dams and reservoirs or river systems [44,45].
- Hypsometric characteristics of any watershed also help to infer the degree of disparity and inequality of composition and processes, which can be the major indices of susceptibility to degradational processes. Moreover, the indices of HI may also determine which measures are needed to manage soil and water conservation. It also analyses the characteristics of storage potential, runoff generation, and response of drainage to rainfall, which can highlight the water resource management process and flood mitigation strategies [46-48].
- HC and HI Highlights on the relief, slope, erosion dynamics and sediment yield of any watershed. The hypsometric analysis detects the relief and slope zones as well as the zones which are more favourable to surface runoff, formation of rills and gullies and accelerated soil erosion rate, especially with sparse vegetation cover. This also helps to prioritize the areas in relation to the protection and stabilization of the slope and measures for the mitigation of erosion. Not only do watersheds with high HI values and steep gradients of curves offer significant potential for the generation of sediment due to active erosion processes. In such cases, watersheds require proper monitoring and management to prevent downstream sedimentation and degradation of waterbodies. Hence, for the study of reservoir sedimentation dynamics and dynamics of sediment transport, HS and HI are the effective tools [49].
- With the help of erosion risk assessment, we can estimate the landscape stability and vulnerability and the degree of erosion risk in the studied basin. This assessment can be helpful for sustainable watershed management, proper land use planning to minimize erosion risk, disaster mitigation plan for slide-prone and flood-prone areas and finally, the holistic environmental conservation [50].

Results and Discussion

A large tract of East and West Medinipur, Bankura, Purulia in West Bengal and covering a small portion of Jharkhand state, the Kangsabati (Kasai) River completes its course before draining into the Bay of Bengal. Undoubtedly, the Kasai, throughout its course, is a significant river basin that plays a significant role in the regional hydro-geomorphology and geomorphology. The present form of study concentrates on the upper-middle course of the Kasai River (From source to Mukutmanipur Dam), which reflects a great diversity of regional uplift, tectonic deformation, climatic variability and resultant gradational processes. From the present study of the upper Kasai watershed, hypsometric analysis highlights the geomorphic evolution of the studied part and helps to explicate the degree of dissection, maturity, erosional history, and tectono- structural influence over time. It also reveals how multi-faceted factors of landscape shaping have furnished the whole water shade from which we can easily infer the geo-chronological history and development of the entire watershed [34].

For the preparation of HC and deduction of HI, topomorphometric calculations, especially, calculated results on relief, slope and topographic analysis were taken into consideration, and for this purpose serial topographic profiles (Figure 3) and their superimposition of the studied course of watershed are explaining deep insight on variation on relief, slope, roughness and degree of dissection of the studied area. Total ten cross sections have been drawn to interpret the variation of relief and gradient of the watershed as well as the steps of landscape evolution. In Figure 3, the profiles on the studied watershed depict the successive stages of landscape evolution with a gradual decrease of slope and elevation in the E–W direction in the diagonal section. For a better understanding of the HC, these differential elevational profiles offer the most effective exposure of the distributional characteristics of vertical and horizontal distance [44]. Moreover, this diagram also depicts

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the geo-chronological evidence of the stages of evolution in micro-watershed level. A marked variation of relief, slope, elevation, roughness, etc., from north-west to south-east within the watershed is clearly observed. In Table 2, necessary extraction and calculation have been done to qualify the nature and characteristics of HC and the extracted values of HI in micro-watershed level of the studied part of the Kasai watershed. The respective areas and elevations (maximum and minimum) of watersheds are extracted in the GIS platform, and the HI of all those micro-watersheds have been calculated following the standardized procedure, and HCs have been drawn for the 16 watersheds to highlight the nature and characteristics of the curves through analyzing the shape and orientation of the curves. Afterwards, HIs have been calculated for all cases, which range from 0.46 to 0.51, denoting a mature stage of landscape evolution with some symbolic presentation of early mature and late mature stages of development. HCs and their superimposition (Figure 3) have been done to represent the existing geo-chronological status relating to the geomorphic evolution of the 16 sub-watersheds in the figure. 04 and 05, which enlighten the following facts regarding the evolutionary status of the micro-watersheds of the upper Kasai watershed [43-45].

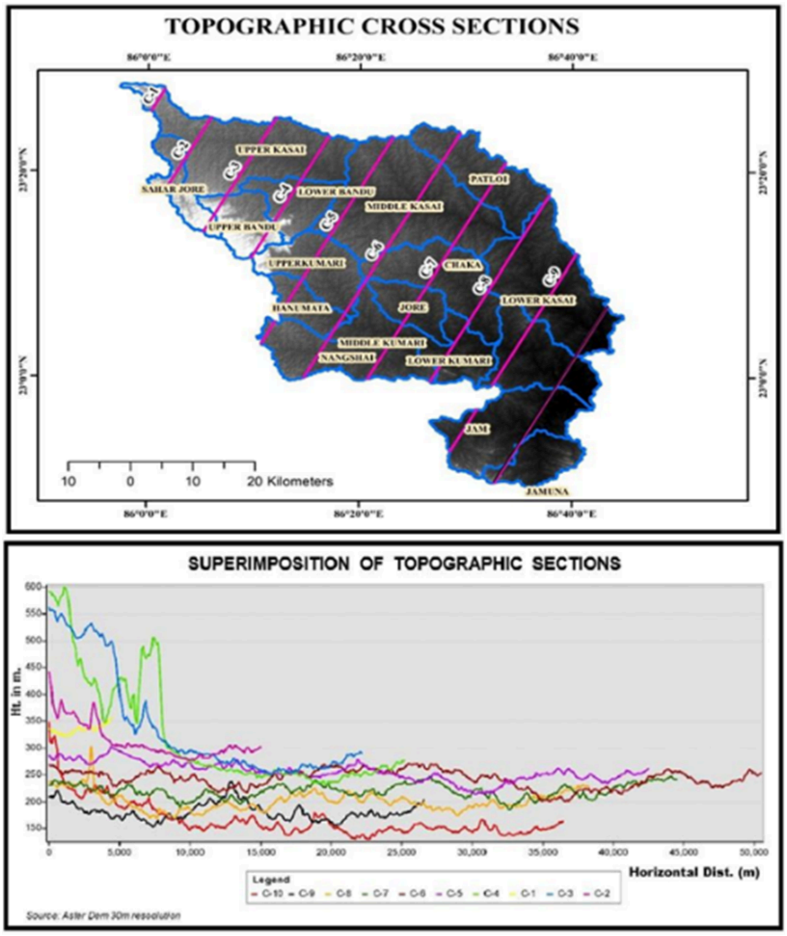

Figure 3. Superimposition of Topographic cross section.

- The surface of the studied watershed represents an erosional plain with rolling topography. Geomorphologically, the area is a part of maturely dissected topography curved by several rivers along with their tributaries. These two major streams, Kasai and Kumari, are marked examples of asymmetric basin floor as they are mostly controlled by lineament and fracture zones from the source and mouth. Moreover, a major part of the studied watershed is also within the structural control of two distinct and nearly parallel shear zones (North Purulia and South Purulia shear zones), which are controlling the across-basin and along-basin exposure within the studied watershed. Kasai, Kumari and their small tributaries are also guided by lineament, fracture, cross joint, etc. [2-5].
- The shape of the HCs (Figure 4) also gives deep insight into the prevailing litho- structure and tectonics in this region. Exhumed hillside slopes, deep weathering surface, rocky exposure, distinct horizontal joints, intrusive granite layers separated by weathered and unweathered rocks, and feldspar-quartz veins (in the Sahar jore, upper Kasai, upper and middle Kumari, Nangsai, upper Bundu, and Patloi sub-watersheds) are the multiple litho-techno-structural elements and also some well-marked prints of neo-tectonic activities within this watershed. Overall, the asymmetric basin exposure of the Kasai and Kumari is also an indicator of a tectonically affected basin. These are also well-supported by the shape of the HC and indices of the HI [5,6].

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- The shape of the HC is qualifying the watershed in terms of geomorphic evolution and giving insight into how far those are departing from continuous evolutionary stages. Their nearly diagonal orientation clearly indicates the qualitative traits of late youth and early maturity (in terms of geomorphic evolution) stage of the sub-watersheds. In this regard, Chaka, Jore, Lower Kasai, Middle Kasai, Upper Bandu, Middle and Lower Kumari Nangsai and Patloi have clear exposure of early maturity and late youth (Tectonically guided) in relation to the shape of the HC. A nearly diagonal shape indicates the balance between uplift and erosion with moderate to low upland topography. Moreover, the nearly convex shape of the curve is the marker of the youthful stage of development with strong litho-structural control (Table 3) [9,10].

Table 3. Standardized table of HI.

Stage Indices of The Geomorphic Evolution	Values of HI
Early Youth Stage	> 0.60
Youth stage	(0.60 ≥ 0.50)
Early maturestage	(0.50 ≥ 0.40)
Mature (Late) stage	(0.40 ≥ 0.30)
Old stage	(0.30 ≥ 0.20)
Senile (Ageing and Worn) stage	(< 0.20)

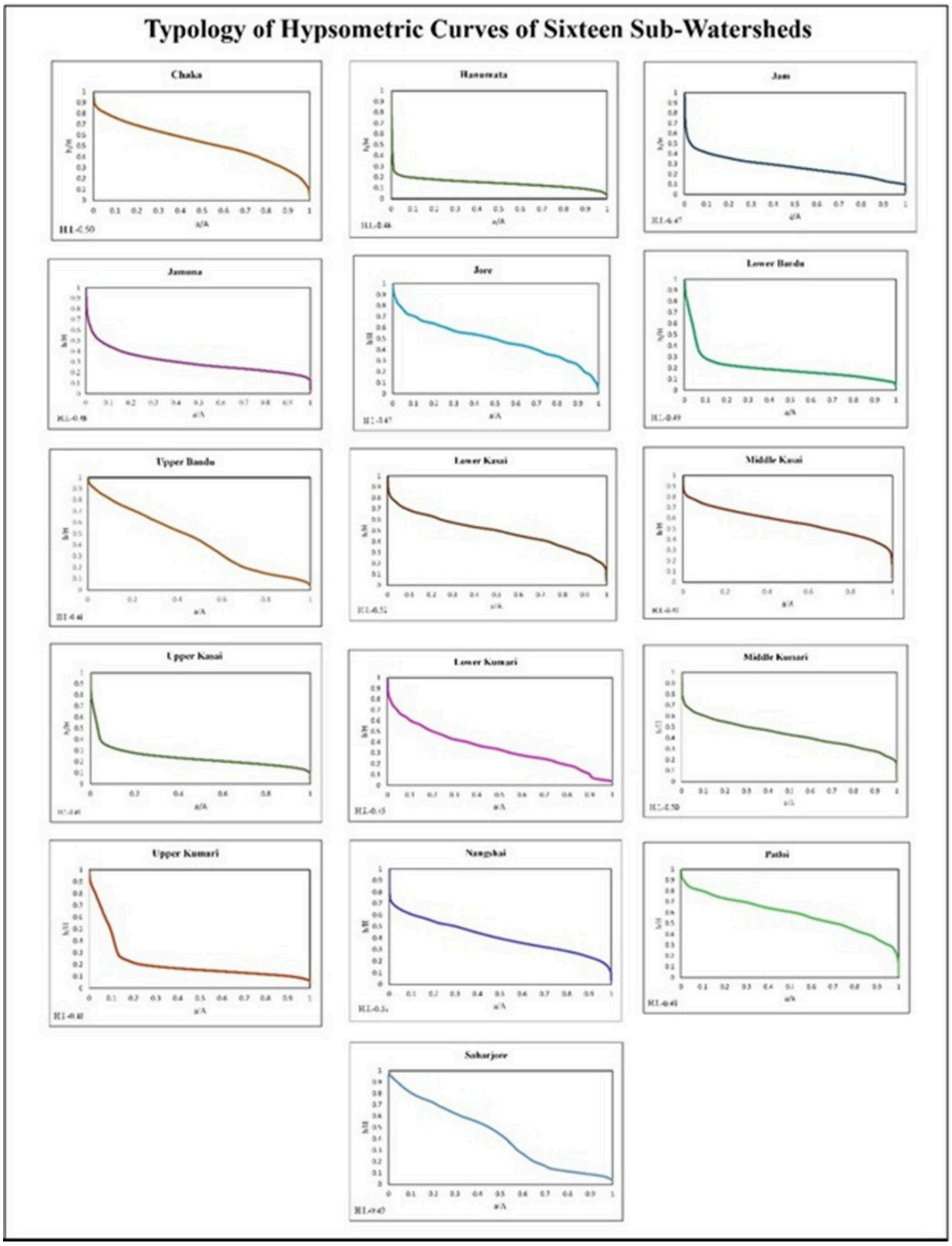

Figure 4. HI (s) of the sub-watersheds.

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Table 4. Estimation of HI and stages of geomorphic evolution.

Sl. No	Sub-Watershed	Elevation(m) Max	Elevation(m) Min	Area(sq km.)	Hypsometric Integral	Max – Min	Geological Stage
1	Chaka	299	149	191.28	0.50	150	YS
2	Hanumata	659	213	71.92	0.48	446	EM
3	Jam	419	98	213.82	0.47	321	EM
4	Jamuna	407	102	92.46	0.49	305	EM
5	Jore	281	172	86.07	0.48	109	EM
6	Lower Bandu	590	215	102.04	0.50	375	YS
7	Upper Bandu	628	265	98.88	0.48	363	EM
8	Lower Kasai	262	102	300.19	0.51	160	YS
9	Middle Kasai	307	153	419.60	0.50	154	YS
10	Upper Kasai	640	193	335.53	0.49	447	EM
11	Lower Kumari	254	121	176.84	0.46	133	EM
12	Middle Kumari	322	127	178.80	0.50	195	YS
13	Upper Kumari	644	210	145.55	0.48	434	EM
14	Nangshai	353	175	180.26	0.51	178	YS
15	Patloi	283	153	175.76	0.49	130	EM
16	Saharejore	608	277	75.95	0.49	331	EM
	Total Watershed	642	174	2844.84	0.49	468	EM

- HI indices of the respective watersheds also highlight various facts on the geo-chronological stages of the watersheds. Table 4 shows the standard indices of the HI with respect to stages of geomorphic evolution. In the present watershed, HI values have been calculated for 16 sub-watersheds, which range from 0.47 to 0.51. Chaka, Lower Kasai, Middle Kasai, Lower Bandu, Middle Kumari and Nangsai have HI values > 0.50, denoting a youthful stage, with marked litho-structural and tectonic influences [35]. The landscape on the aforesaid surfaces represents early stages of erosion, stream incision and traits of uplifting surface carved by the river system. Though HI values are comparatively high, like the youthful stage, the whole landscape is remarkably subdued with higher relative relief and a large proportion of lower elevations. The hydro-geomorphic processes, such as sediment transport, a wide valley floor, and deposition, are commonly evident in the landscape [2].
- Superimposition of HC (Figure 5) has been done to highlight the geomorphic status of the sub- watersheds. As observed from the superimposed HC, it has been assigned that the inter-curve axis(A---C) for the two extreme curves is moderately high, which highlights the nature of intermediate stages of the geomorphic evolution of the sub-watersheds. It has also been suggested that the curves do not uniformly direct the stages of geomorphic evolution; complex geomorphic processes are observed. The curves reflect tectonic activity, a high rate of water divide erosion with high rainfall, faster erosion rate, factors of weathering resistance, relative balance between elevation and land area, and greatly influence the shape of the curve as well as the HI. The differential value of HI is also crucial for qualifying the erosional history, neo-tectonic processes, and sediment dynamics of the present watersheds, which may also encourage hydrological as well as landscape modelling and environmental planning and management [11,12].

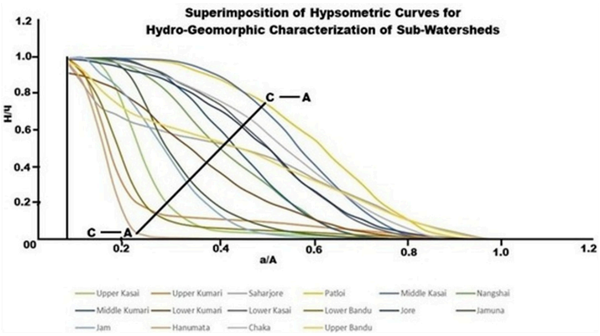

Figure 5. Superimposition of the HC of sub-watersheds.

The hypsometric analysis of the sub-watersheds of the Kangsabati basin provides essential inputs regarding the geomorphic evolution and hydro-geomorphic characterization of the entire watershed. The entire watershed represents early maturity (like youth) to late mature stages of evolution with resistant rocky exposures, extensive erosional plain and almost stable landscape, which are mostly crucial for holistic watershed management, addressing control of erosion, effective flood plain management and sediment control strategies [49]. Such a pattern of analysis may also be helpful for the estimation of the river discharge pattern, sediment load, water divide erosion, flood risk assessment and resource management as well. Notwithstanding that, understanding the HC and HI of the present sub-watersheds, the erosion risk assessment of the respective sub-watersheds is also estimated, and the shape and slope of the curves and values of the HI are most helpful in this regard. Apart from that, relief, slope, lithology interface extracted from the area-elevation analysis and topographic analysis are also the most critical drivers to assess the erosion risk of the sub-watersheds [20,21].

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Finally, the following points may be entrusted to estimate the erosion risk, vulnerability to erosion and prioritization of sub-watersheds after understanding the erosion-prone areas of the sub-watersheds, because this is a major issue against the holistic development and management of the watersheds. The nature, characteristics and qualitative and quantitative properties of HC and HI can be the determinant in this regard [25]. Findings are as follows.

- HI in the present watersheds reflects the relationship between the proportion of respective watershed area and elevation, and as a result extraction of HC may reflect the extent of erosion. Convex and convexo-concave curve (representing youth and late youth stage), explaining the comparatively lower rate of erosion due to higher elevation and bare rocky surface. But steep hill and valley side slopes and rolling uplands gradually accelerate runoff velocity, promoting active sheet erosion, formation of rills and gullies, and other degradational processes are also very active, so, high to moderately high erosion risk is resultant [4,5].
- The sub-watersheds with 'S'– shaped HC are generally represented by maturely dissected topography with moderate to high relative relief reflecting moderate to moderately low erosion, as it represents the interface between the highland and lowland areas [38,3]. Higher rate of sediment yield from the upslope promotes a higher amount of sediment load along the precipitous slope and stream channels. So, moderate to moderately low rates of erosion are observed with higher risk in the crest slope, mid slope and moderately steep valley side slope, but other stable and lower elevated areas have low risk in comparison to the previous [15,16].
- The concave shape curve reflects subdued relief with low to moderately low elevation allows extensive erosion in the rolling or inclined surface. But the rate of erosion is negligible in the downstream areas, where sediments are deposited and treated as residual plain zones. Usually low to very low erosion risk with predominating deposition and siltation issues [19,20].
- The HI is also a remarkable indicator for assessing the erosion risk of the watersheds. The HI quantifies the residual proportion of elevation in the watersheds in relation to initial relief. The values of HI for different watersheds are a significant indicator of differential erosion risk of the watersheds. The HI is the quantitative indicator of the erosion risk assessment of the watersheds.
- High values of HI (>0.50) represent the rejuvenated relief with a comparatively higher proportion of elevated land with steep slope and active erosional processes. Higher relief and steep slope entrusted by higher energy promotes a higher rate of surface runoff, encouraging rills, gullies and rivulets, also reflecting moderate to moderately high erosion risk, especially in the higher surfaces where shallow and loose soil layers are dominating [35,36,50].
- Most of the watersheds in the studied region reflect the HI values below 0.50 but > 0.45, which are characterized by maturely dissected to mature landscapes in landscape evolution. These curves with stipulated HI values represent complex topography with varying relative relief, configuring a residual or subdued landscape with gently inclined to gentle slope and low relief. Slopes have a moderate erosion process with sheet and rill erosion, and lowlands are almost stable with a negligible rate of erosion. Erosion risk is moderate to moderately low and concentrated, especially in the channels and valleys.

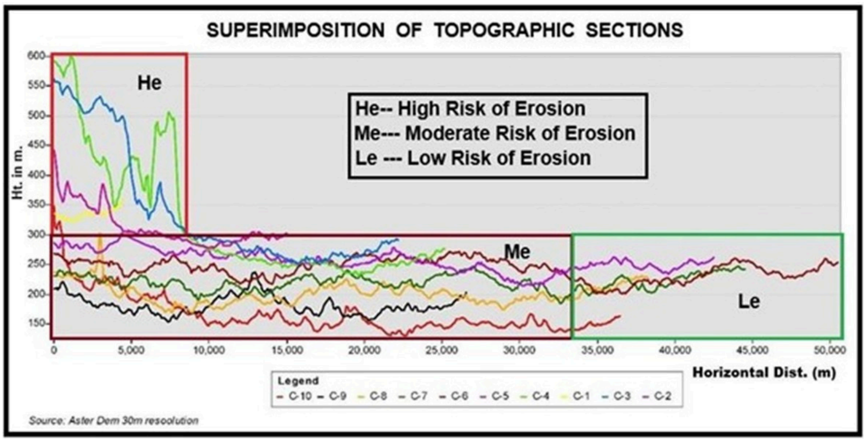

Figure 6. Relief, slope and erosion risk – a graphical correlation.

Table 5. Hypsometric analysis in relation to erosion risk assessment.

HI	HC (Shape)	Affected Sub-Watersheds	Erosion Risk
0.46 – 0.48	Concave-convex, Concave-straight	Jore, Hanumata, Upper Bandu, Upper Kumari, Lower Kumari, Jam	Moderate to Low
0.49 – 0.50	Concave-convex, Concave-continuous	Chaka, Jamuna,Lower Bandu, Middle Kasai, Upper Kasai, Middle Kumari, Patloi, Saharjore	Moderate to Moderately High
> 0.50	S - Shape	Lower Kasai, Nangsai	Moderately High

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Apart from that, hypsometric analysis indirectly incorporates relief, slope, roughness and differential elevation status of the watersheds, which are significant operators of erosion risk (Figure 6). Steep to moderately steep slope found in the watersheds with moderately high HI values, leading to a higher erosion rate in comparison to gentle to gently inclined slopes found in subdued part in the watersheds with moderately low to low HI and are represented as comparatively low erosion risk. Moderate to moderately high sediment yield suggests balanced sediment production and transport, as well as erosion and deposition processes occurring, which need proper management policies to prevent accelerating sediment downstream and siltation issues as well.

Conclusion

Hypsometric analysis in the present watersheds be a significant tool to prepare erosion mapping for prioritizing watersheds, land use planning, flood water and sediment management and in combination with other geo-morphometric, topometric and hydrological parameters, refinement of the erosion risk assessment will be possible for sustainable and holistic development of the Kasai watershed. The analysis of HC and HI of sub-watersheds is also an effective approach to target and process the erosion-prone zones for justified watershed management strategies to minimize the rate of degradation of the watersheds and to sustain the geomorphic stability.

Disclosure Statement

The Authors declare that there is no conflict of interest.

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