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Morphometric Analysis of Vandaman Eru Watershed, Southern India Using Remote Sensing and GIS

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Abstract- Morphometric analysis is a crucial part of the complete evaluation of Morphometric analysis are significant processes in hydrology, landform evolution and environmental processes at drainage basin scale. The morphometric parameter of stream, area and relief aspects obtained through the integrated remote sensing (RS) and geographic information system (GIS) techniques will helping to understand the hydrological behaviour, erosional vulnerability and groundwater recharge potential of a u-shaped Vandaman Eru Watershed (508.98 km2). This watershed is semi-arid, and we can observe a branching drainage pattern that relates to lithological homogeneity with little tectonic distortion. This study revealed the significant spatial variability in drainage density throughout the watershed. The watershed-integrated drainage density is calculated on the basis of total stream length (1,855.85 km) compared with total basin area (508.98 km2) computes at 3.65 km/km2 which indicates fine dissection and a high surface runoff generation capacity that is characteristically found in higher-altitude, peripheral terrain. Drainage density in the context of geomorphic region is 0.23 to 0.69 km/km2 for alluvial plains landform with lowest dissection and high infiltration potential at sub-basin level compared to other geomorphic units. This dichotomy of low sub-basin drainage densities versus high basin-scale drainage density is indicative of the criti-cal spatial heterogeneity of the watershed, one which will be explicitly differentiated throughout this manuscript. Important key linear, areal and relief morphometric parameters extracted for understanding channel development mechanism, basin geometrics, runoff potential and erosion susceptibility. The results demonstrated a strong inverse exponential correlation (R2 = 0.81) between the drainage density and infiltration rate within zones defined spatially. Establishing the hydrological segregation controlled by spatial variability in drainage density across the watershed via a holistic morphometric analysis and identifying valley fills and pediplain zones as regional-focused target sites for artificial groundwater recharge.

Keywords: Bifurcation ratio · Drainage density · Stream frequency · Semi-arid hydrology · Watershed management · Pennar basin.

I. INTRODUCTION

Morphometric analysis offers crucial quantitative descrip-tion of the geometry and topology of drainage basins and therefore forms a bedrock element of contempo-rary hydrology. A systematic evaluation of basin shapes, stream order, drainage density and relief components enables inferences on hydrological regime, sediment yield, flood hazard and susceptibility to erosion. Such knowledge is especially useful throughout Southern India and similar areas with varied weather and complicated relief. In the last 20 years, remote sensing and geographic information system integration has significantly propelled these studies [1–3].

In recent years (over the past decade), morphometric analysis of river basins in semi-arid hard-rock terrains (e.g. Southern India) has attracted considerable inter-est. Studies have demonstrated the utility of GIS-based morphometric parameters to characterize hydrological response, mask areas prone to erosion, and prioritize zones for groundwater recharge [1, 2, 4] in Pennar basin sub-basins [4], Cauvery sub-basins [1], and Vanniyar water-shed respectively [2]. Recent progress has been made on multiple fronts, such as the utilization of high-resolution DEMs (ALOS PALSAR, TanDEM-X) to achieve better delineation [5], machine learning algorithms for more precise calibration of hydrological parameters, as well as multi-criteria methods, combining morphometric indices and land use and soil information assets to carry out a complete watershed prioritization. Drainage density has become one of the most important parameters for quan-titative geomorphology linking geological permeability, efficiency of surface runoff and ground water recharge potential in similar hard-rock semi-arid watersheds [6–8]. However, the majority of current studies describe entire watershed average morphometric measurements while not presenting sufficient spatial variability in parameters across diverse terrain types, thus restricting their applica-bility for site-specific management responses.

Morphometric parameters can be classified into linear, areal, and relief characteristics according to specific corre-lations. The bifurcation ratio (Rb) is a common descriptor of the framework and is defined as the number of stream segments of a given order divided by the number of seg-ments with next higher order [8], thus capturing drainage network's hierarchical organization. High bifurcation ratio indicates structural control, perhaps by geological fault or litho logical change, while low bifurcation ratio results from more uniform geological scenario [1, 9].

Drainage density and stream frequency, as essential areal measures, indicate the intensity of stream dissection and the underlying materials' permeability. High drainage den-sity reflects impervious subsoils with high runoff potential (> 1.5 km/km2), while low drainage density indicates poten-tial for groundwater recharge [9–11].

While there are a number of major studies emerg-ing on the large watersheds of Southern India, relatively little effort has been focused on (smaller scale) tributar-ies, that nevertheless contribute to significant hydrologi-cal nodes. Significance of the research: There has been no remote sensing DEM-based morphometric study up to now in a single work for the Vandaman Eru Watershed, and its hydrological response features including but not limited to erosion hotspots and recharge capability are yet uncalculated. Moreover, stream ordering methods are usu-ally based on regional studies that present morphometric parameters at basin scale without investigating the spatial variability of drainage density for the purposes of site-specific water management.

Thus, the basically objective of this study is to analyse the morphometric analysis of Vandaman Eru Watershed using remote sensing and GIS techniques. Specific objectives are: (i) Mapping and char-acterisation of the drainage network, estimation of linear, aerial and relief morphometric parameters; (ii) Analysis of the controls imposed by geology and geomorphology on the drainage pattern and hydrological response; (iii) Exam-ining spatial variability in drainage density and infiltration capacity across a watershed as well as sub-basin scale; iv. Recognising priority zones for soil conservation through artificial groundwater recharge through an integrated mor-phometric approach.

Study Area

The Vandaman Eru Watershed is situated in the Southern Rivers region of Andhra Pradesh, within Sri Satya Sai Dis-trict, South India, covering an area of 508.98 km2. It is geo-graphically located at the latitude of 14°05'N to 14°25'N and longitude of 77°55'E to 78°09'E (Fig. 1). The water-shed is situated in a semi-arid climatic region and consists of assorted geological segments out of which the rocks are predominantly made up of dolerite dykes, grey biotite gran-ite and meta-andesite (Fig. 2). Locally, the topography is about 760–890 m AMSL (above mean sea level) undulating.

Climate

The Vandaman Eru Watershed is located in a semi-arid climatic zone (Köppen classification BSh). Mean annual rainfall varies from 550 to 700 mm, with around 80% of precipitation occurring during the southwest monsoon sea-son (June–September). The northeast (October–Decem-ber) monsoon adds another 10–15% as intermittent light rainfall events. Mean annual temperature varies from 25 °C in southern areas to 35 °C in northern regions, and summer maxima can exceed 40 °C during the months of April–May. Potential evapotranspiration (PET) ranges between 1,400–1,600 mm/year, significantly higher than rainfall during the year with an aridity index of around 0.40–0.50 (semi-arid classification). This region is prone to drought, as evidenced by approximately 3 out of every 10 years experiencing meteorological drought (IMD records). These climatic conditions primarily dictate the watershed hydrological behavior: extreme monsoon precipitation generates elevated surface runoff on steep slopes with low-permeability substrates, while the long dry season constrains natural groundwater recharge to the short monsoon period.

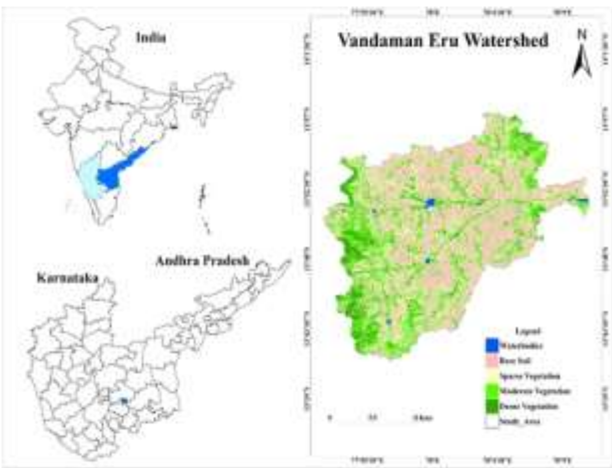

Fig. 1 Location map: Vandaman Eru Watershed, South India

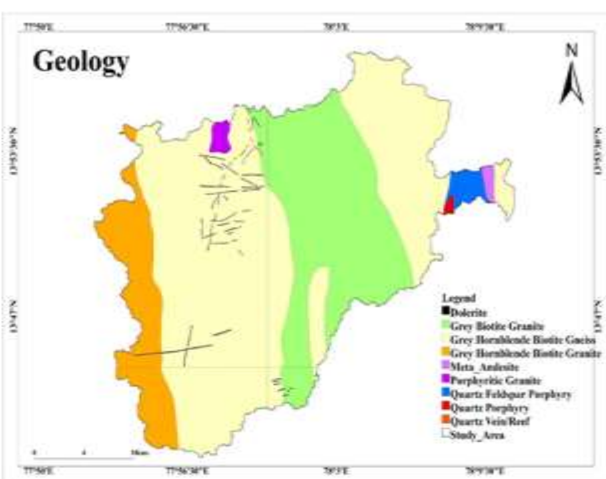

Fig. 2 Geology map of the Vanda-man Eru Watershed, South India

The watershed has a dendritic drainage system as its main type, with significant spatial heterogeneity. Localized drainage density values for sub-basins are equal to 0.23–0.69 km/km2, so alluvial plains and gently undulating central areas show ample infiltration and recharge capacity, promoting the availability of water resources in aquifers (Fig. 5d). Locally, in high-order stream networks and steeper slopes the drainage densities ranged from 1.2 to 2.8 km/km2 at higher-elevation terrain during October–December 2023. The drainage density of 3.65 km/km2 reflects the watershed-integrated morpho-metric signature over all landscape classes and stream orders within the basin boundary.

II. METHODOLOGY

Morphometric analysis of the Vandaman Eru Watershed was performed using an integrated geospatial platform, includ-ing Remote Sensing (RS) and Geographic Information Systems (GIS) and Digital Elevation Models (DEMs). The methodology was organized into a sequential, reproducible protocol with four primary phases: (1) Data Acquisition and Preprocessing, (2) Hydrographic Feature Extraction, (3) Quantitative Parameterization, and A flow diagram of this workflow is shown in Fig. 3.

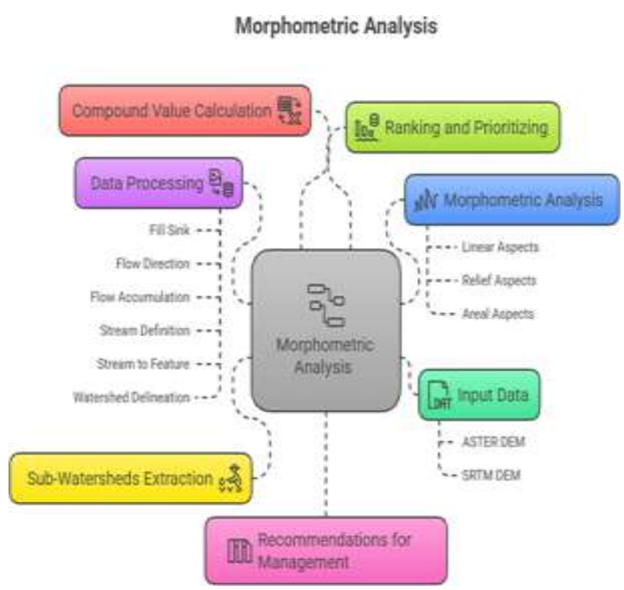

Fig. 3 Methodology for the Mor-phometric analysis of Vandaman Eru Watershed, South India

III. DATA ACQUISITION AND PREPROCESSING

Geometric Correction

Geometric correction is the process of aligning search data models accurately along an established standard line on the geographic reference plane and with respect to one another which will here be topographic maps. Georeferencing is the process of providing real-world coordinates to raster images such as scanned toposheets so that they can be integrated with satellite imagery and elevation data. SoI topographic maps were converted to the WGS 1984 UTM reference frame. The process eliminates distortions caused by scan-ning together with original cusping projections through means of a network of ground control points (GCPs), where prominent map traits are corresponded to a set of catalogued known geodetic coordinates [4, 12]. By ensuring that drain-age discontinuities, elevation contours, and basin peripher-ies can be overlaid without positional error on Sentinel data or the SRTM DEM, it ensures programmatic correction.

DEM Processing

DDEM processing, allowing digital elevation models to better reflect hydrological processes. Miscellaneous pro-cesses include sink filling to remove false depressions, and flow direction assignments to derive possible trajectory paths of runoff, along with flow accumulation for the pur-pose of obtaining aggregate inflow for each raster cell. The eight-direction (D8) algorithm is the standard representa-tion: for each cell, it assigns the local maximum gradient toward one of eight possible cardinal classes (N, NE, E, SE, S, SW, W and NW). The first operation in ArcGIS Pro was sink filling to provide a continuous drainage surface. Flow direction was produced with the D8 algorithm and then a series of accumulation analyses were performed to tease out the land in each location that contributed to the catena, thus identifying candidate channel networks [12–14] This procedure is essential to achieve the precision required for reconstructing drainage systems and for hydrological catch-ment delineation (Fig. 3).

Stream Thresholding

Stream In stream thresholding, the minimum upslope con-tributing area required for the existence of a continuous channel to persist is determined. Using this criterion, it fil-ters out transient flows in the stream layer. The threshold calculation uses flow accumulation counts from an eleva-tion model. In particular, an area threshold of 1 km2 was applied: raster cells with accumulation counts ≥ 1 km2 were indicated as stream initiation points while underlying cells were ignored. In this framework, there exists a simple quan-titative criterion (which we have tested in the semi-arid terrain of Southern India) that ensures all branches which possess significant geomorphic relevance are retained while any unneeded detail is eliminated, producing much more stable responses from the resulting channel net. As an exam-ple, Mangan et al. (2019) found that their threshold results would produce a stream geometry for the Kandaihimmat watershed fully consistent with field measurements.

Watershed Delineation and Stream Network Extraction

Standard hydrologic algorithms in a GIS environment were used to delineate watershed divides. Standard flow-accu-mulation routines then generated the stream skeleton and ordered it using Strahler [15] hierarchical scheme. Tidal reaches of the Vandaman Eru showed that when moving from terminal first-order tributaries to the apex main stem channel, the total hierarchy revealed a magnitude of sixth order. The resulting dendritic pattern of tributary develop-ment also supports a lithology of uniform hydraulic conduc-tivity and little to no tectonic effects [16].\

Morphometric Parameters

Morphometric parameters are quantitative measurements used to evaluate the shape and characteristics of landforms, typically classified in three main categories, including linear, areal, and relief parameters. Parameters of the lin-ear type, such as stream length and order for drainage net-works and lineal features in landforms; Also included are the area parameters or two-dimensional indicators such as basin area, perimeter and drainage density that summarize the extent of the landform in space. Relief parameters repre-sent the three-dimensional features of terrain by delivering vertical variation and horizontal spatial variability, such as elevation, slope, and ruggedness. This classification is help-ful in systematically investigating geomorphological and hydrological characteristics of watersheds and landscapes.

Linear Parameters

Linear parameters are linear dimensions, including stream length and stream order, that quantify drainage network properties and linear landform features.

Stream Order Stream order offers a systematic method for ranking watersheds within a drainage network by incorpo-rating both longitudinal position and tributary bifurcation. Of several existing methodologies, the implementation of Strahler order, originally proposed by Arthur Strahler in 1952 continues to be widely used within hydrological lit-erature [14, 17]. In this system, independent, non-tributary headwaters are designated as first order, while subsequent tributaries append numerical orders cumulatively to each other only after convergence with one another whereupon the order of the resulting channel equals the highest order number tributaries and that of equal converging sources yielding advance to a higher integer.

The merge of two streams in the same order forms a stream of the next higher order. For instance, two first-order streams that join become a second-order stream; two second orders that merge create a third order (Fig. 4). Stream order reflects essential water-shed attributes such as drainage density, network complex-ity and hydrological behaviour. To accommodate the water inflow from multiple lower order tributaries, higher order streams usually have wider channels with deeper water and slower flow velocities and transport a larger volume of flowing water [18].

Stream Number The number of streams (Nu) is the total number of stream segments for each order within the drainage network. This parameter is in line with Horton's Law of Stream Numbers which mentions, that the num-ber of streams plotted against stream orders are geomet-ric [19]. This principle is demonstrated well in the data you provided with stream numbers decreasing from 1,420 (first-order) to 1 (sixth-order), reflecting the expected neg-ative relationship between stream order and stream fre-quency (Table 1). Horton conducted an empirical analysis,

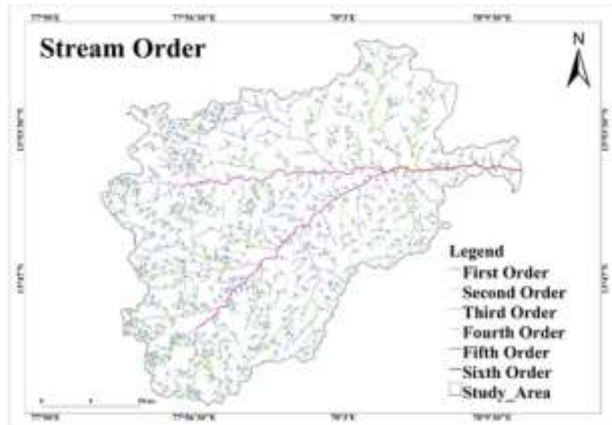

Fig. 4 Stream order of the Vanda-man Eru Watershed, South India

Table 1 Linear aspects of the Vandaman Eru Watershed

Stream order	*Nu*	*Rb*	Total stream Length	Mean stream Length (km)	*RL*
I	1420	6.31	1041.37	0.733	—
II	225	6.43	410.88	1.826	2.49
III	35	3.18	186.34	5.324	2.92
IV	11	5.50	113.98	10.362	1.95
V	2	2.00	83.35	41.675	4.02
VI	1	—	19.93	19.93	0.48
Mean Bifurcation Ratio (*Rbm*) = 4.68					
Nu number of streams, *Rb* bifurcation ratio, *RL* stream length ratio, *Rbm* mean bifurcation ratio;					

showing that the number of streams declines systemati-cally with increasing stream order, generally following a geometric progression with a bifurcation ratio of around 3–4 for natural drainage systems.

Bifurcation Ratio (Rb) The bifurcation ratio is a dimension-less number that describes the amount of rivers (or streams) of any given order class, that branch off into smaller water-ways of one higher order essentially comparing how many older tributaries feed larger younger channels with the total number of second river systems they serve. This ratio pro-vides insight into the overall geometry and organizational complexity of a river's tributary system.

Rb = Nu/Nu + 1

where, Rb = Bifurcation ratio Nu = No. of streams and Nu + 1 = No. of stream at next higher order.

Mean Bifurcation Ratio (Rbm) The bifurcation ratio is a mean that quantifies the way the branching of streams in a basin progresses from one order to the next, and it takes an average of the ratio between a number of streams of one order to those belonging to another higher order. Such an average quantity gives therefore a brief measure for the overall branching geometry of the drainage basin. It allows for comparisons across watersheds by depicting the order of complexity in a hierarchy.

Total Length of Streams (km) One such indicator is total stream length, the sum of lengths of individual stream seg-ments across all orders in the drainage hierarchy. This com-posite metric reflects the extent of waterway channelization that has occurred throughout the watershed. Water Flow and Sediment Movement Not only is stream length an important characteristic but also the flow of water. However, topo-graphic and geological characteristics can lead to certain cases where this trend does not hold true. The total stream length is crucial in the computation of drainage density, revealing the extent of landscape dissection and surface run-off pattern.

Mean Length of Streams (km) Mean stream length (Lsm) is the ratio between total cumulative stream length of a given order and total number of stream in this order. This parameter shows the typical size of elements in the drainage network.

Lsm = Lu/Nu

where,

Lsm (mean stream length), Lu ≡ total stream length of order u, and Nu ≡ total number of stream segments of order u.

Stream Length Ratio (RL) Horton [6] defined the stream segment length ratio as the mean stream length of a given order divided by the mean stream length of next lower order. This dimensionless parameter describes the geometric scal-ing of stream lengths.

RL = Lu/(Lu − 1)

Horton [6] Law of stream lengths states that in a geometrically ideal drainage network the ratios between streams length are essentially constant for successive orders. Such differences from this pattern suggest variation in slope, topography control and/or geological control. According to Pande [20], stream length ratios are useful in identifying geomorphologi-cal development stages as well as structural controls of water-sheds. An increasing and continuous trend, from lower to higher order, means a strongly geomorphological stage of the valley development and nontransitive characteristics, absolute instability implies geological and topographical features.

IV. AREAL PARAMETERS

Basin Area (A) The catchment area, also referred to as the basin area, is defined as all of the land surface where rain-fall eventually drains back into a common outlet such as river, bay or lake. This coverage is delineated by the tallest landforms surrounding the stream and riverbeds, which col-lectively form a natural boundary called a watershed divide. The total basin area is crucial to the fields of hydrology and geomorphology because it defines the scale at which water and sediment transport processes within the watershed occur.

Form Factor (Ff) Form factor (Ff) a commonly dimension-less morphological index used to represent morphology typology of the within a drainage basin. This ratio indicates the narrower shape or a more round; these shapes have dif-ferent implications in terms of hydrological processes and/ or flood generation. In the theoretical extreme, for a circu-lar basin this will tend toward a form factor of unity, while more elongated geometries achieve much lower values.

$$F_f = \frac{A}{(Lb)^2}$$

Elongation Ratio (Re) Elongation ratio, a dimensionless measure of the shape of drainage base with respect to max potential compactness. It is obtained from the ratio of the diameter of an equivalent circular geometry, with basal area equal to that of the basin, and its maximum longitudinal axis referred to as Lb. The resultant value provides a concise measure of how stretched out the basin is compared to being circular. A basin encompassing an and Re value near unity approximates a circular outline for most efficient hydrologic path travel to concentrate runoff. Deviations from that ideal with lower and lower Re values indicate greater elongation and associate with more prolonged hydrologic response times and spatial runoff dissipation.

$$Re = \frac{\sqrt[2]{\frac{A}{\pi}}}{L_b}$$

where:
AA = Basin area (km2), LbLb = Basin length (km) and ππ = 3.1416 (constant).

Circularity Ratio (Rc) The Circularity Ratio (Rc) is another morphometric parameter that quantifies how much the shape of a drainage basin deviates from a perfect circle. This index is significant in providing indication or insights to geomor-phological maturity and determining dominant factors (sex. underlying lithology, structural control) active in shap-ing watershed. The circularity ratio of a basin approaches 1.0 for a nearly circular basin, while lower values indicate elongation and irregularity of the basin.

Because of the relatively even distribution of contributing area around the centre, a circular basin is generally regarded as providing more efficient flow-channeling toward its outlet and thus yielding higher peak flows. Elongated or irregularly shaped basins have more prolonged hydrographs and smaller peak discharges.

The circularity ratio is calculated as follows:

$$R_c = \frac{4\pi A}{P^2}$$

The formula for circularity ratio is as follows: Where: AA = Total basin area (km2), PP = Perimetro de la cuenca
(km) and 26ππ = 30.17586056 Mathematical constant,
≈3.1416.

Drainage Density (Dd) Drainage density (Dd) is one of the most basic morphometric indices which has been used in hydrological and geomorphological research. It combines all the lengths of streams and rivers in a watershed divided by the total area of that watershed. Dd represents the degree of stream network development in a basin landscape. This refers to a measure of how well or poorly any given water-shed is drained. It also indicates the extent of fluvial dis-section and runoff generation efficiencies, as well as the transport of water within surface drainage channels.

The formula to calculate drainage density is:

$$D_d = \frac{\Sigma \text{ Length of all streams}}{A}$$

Stream Frequency (Fs)

The stream frequency measures the distribution of channel segments in a watershed and is derived by dividing the total number of channel segments by the area they occupy. This index indicates a relatively loose, “un-connected” network of watercourses or a tightly woven, “connected” drainage system; thus revealing both the underlying hydraulic rout-ing and the influence of PT descriptors on parent rock and sediment assemblages.

$$F_s = \frac{\text{Total number of stream segments}}{A}$$

Relief Parameters
One of the most important and significant characteristics of watershed morphometry are relief parameters. These met-rics capture the vertical depth of a drainage basin and thus provide a

measure of topographic heterogeneity, the gravi-tational potential energy available in flowing water, and the erosive potential of the basin. In hydrology and geomor-phology, they are essential for predicting runoff response, slope stability and soil susceptibility to erosion.

Basin Relief (Bh) The overall basin relief is the vertical height between the maximum and minimum elevations in the water-shed. As the primary index of relief, basin relief provides a concise summary of the vertical organization of the drainage basin that propagates to affect both runoff velocity and the mechanisms of bedload erosion and transport.
Total Basin Relief (H)= Hmax − Hbm

Relief Ratio (Rhl) The Relief Ratio (Rhl) is the ratio of relief to basin length, Used to understand the potential for erosion. It is computed by the formula: Rhl = H/Lb.

where,
Rhl: basin relief; Lb: basin length.

Spatial Analysis of Drainage Density
Considering the heterogeneous hydrological topography of the watershed, a dual-scale proportional analysis was car-ried out to account for the spatial variability in drainage density. (a) Network-integrated Dd: the total stream length in all orders (1,855.85 km) divided by the total basin area (508.98 km2), result of the basin-wide Dd was 3.65 km/ km2. (b) Sub-basin Dd: The watershed was divided into geomorphologically homogenous sectors according to slope classes (15°), geomorphic units (alluvial plains, pediments, dissected hills) and geological mapping. Local Dd was cal-culated for each zone as the total stream length contained in that portion of the watershed divided by its area. This process unveils the spatial architecture of drainage dissec-tion hidden in a single basin-wide value and provides vital context for defining regions of elevated infiltration capacity with low runoff potential.

V. RESULTS AND DISCUSSIONS

Linear Parameters

Stream Order (w)
The study watershed demonstrates a sixth-order drainage system with a total of 1,694 streams. The distribution shows a clear hierarchical pattern with 1,420 first-order streams (83.8% of total), progressively decreasing to a single sixth-order stream representing the main channel outlet.

Stream Number
The number of streams (Nu) represents the total count of stream segments within each order of the drainage network. This parameter follows Horton's Law of Stream Numbers, which states that stream numbers tend to form a geomet-ric series when plotted against stream order. The provided data demonstrates this principle clearly, with stream num-bers decreasing from 1,420 (first-order) to 1 (sixth-order), following the expected inverse relationship between stream order and stream frequency (Table 1). According to Horton's empirical analysis, the number of streams decreases system-atically with increasing stream order, typically following a geometric progression with a bifurcation ratio of approxi-mately 3–4 in natural drainage systems.

Bifurcation Ratio (Rb)
Bifurcation ratios in natural river systems are most often found within the interval 3–5, with the range of 3.5 to 4.0 dominant in highly developed mature networks. While ratios below 3 are rarely seen, the current analysis shows values over 6. The ratio reveals certain aspects around the drainage morphology, geological influence that drives it and the pattern of runoff across its range. High ratios tend to indicate strong structural control, such as faults or joint sys-tems – low ratios show more homogeneous physical envi-ronments.” This dataset gives ratios that range from 2.00 to a maximum of 6.43, notable values being the consecutive recorded stream orders of 6.31, 6.43, 3.18, 5.50 and mini-mum value (consecutive order) is observed at ratio of around 2.00 which signifies moderate control by geology could be observed influencing on spatial distribution of stream orders as shown in table no:1.

Mean Bifurcation Ratio (Rbm)
From the analysis, an overall mean bifurcation ratio (Rbm) of 4.68 was obtained (Table 1), indicating

moderate branch channel development and characteristics conforming to the form expected for geomorphic landforms [21, 22].

Total Length of Streams (km)

Stronger total lengths in smaller orders are generally associ-ated with high relief, steep slopes, and eroded terrain. The watershed had total stream lengths of 1,041.37 km (first-order) to 19.93 km (sixth-order), with a cumulative total of all orders equal to 1,855.85 km (Table 1).

Mean Length of Streams (km)

Mean stream length typically increases with stream order, reflecting the progressive increase in channel size and drain-age area [23]. This parameter helps understand the topo-graphic control and surface characteristics of the watershed. The calculated mean stream lengths increase from 0.733 km (first-order) to 19.93 km (sixth-order), with the exception of a decrease in the sixth-order (19.93 km compared to 41.675 km in fifth-order), indicating possible topographic or structural controls (Table 1).

Stream Length Ratio (RL)

Significantly, stream length ratios for all sequential order transitions are variable: 2.49 for 1st- to 2nd-order streams; 2.92 for 2nd- to 3rd-order streams; 1.95 for consecutive up-stream orders (3rd to higher); and only moderate value of ~ 4.02 for the last order, i.e., highest reaching point derived from river networks in the hierarchy representing watershed structure controlled by regional geomorphic set-tings (Table 1).

The morphometric survey indicates a devel-oped sixth-order drainage network conforming with the characteristics of undisturbed watersheds. The mean bifur-cation ratio of 4.68 fits nicely into the 3–5 range common for such systems, indicating that geological structure is having a small but non-negligible impact. Lengths of each stream, on average longer at each subsequent order to the fifth and shorter by sixth, suggest topographic variations or factors of structure that directed development of the master channel. The stream length ratios, in turn, follow the geometric pro-gression that Horton outlined in 1945, although persistent deviations in several of the cases indicate that local geology and relief are also influencing the geometry.

VI. AREAL PARAMETERS

Basin Area (A)

A total basin area at 508.98 km2 for the Vandaman Eru watershed has been computed (Table 2). This extensive sur-face demonstrates the ability of a drainage system to inter-cept precipitation and direct surface runoff sourced from a large landscape area towards its discharge points [24].

Form Factor (Ff)

The value of the derived factor in case of Vandaman Eru watershed is 0.35 which indicates a comparatively lower (Table 2). This result clearly indicates a preference for degrees of elongation rather than stilliness. Such morpho-logical characteristic has a significant impact on the time distribution and spatial variability of runoff, especially in cases of extreme rainfall events.

$$F_f = \frac{A}{(L_b)^2}$$

Elongation Ratio (Re)

The elongation ratio calculated for Vandaman Eru water-shed is 0.67 which comes within the range of classification scale of 0.5 to 0.7, watershed with a value of 1 would be perfectly circular, while a value greater than 1 indicates an elongated or stretched watershed along its length. In com-parison to circular watersheds of equal area, moderate elon-gation of the watershed enables more uniform deposition of surface runoff towards the mainstream; hence, empirically a slightly distributed and lower magnitude peak flood dis-charge. Table 2 summarizes the morphometric parameters in detail that underlie this classification.

Table 2 Areal aspects of the Vandaman Eru Watershed

Basin area km^2	Perimeter (km)	Length (km)	Form factor	Elongation ratio (Re)	Circularity ratio (Rc)	Drainage den-sity (Dd)	Stream frequency	Drain-age texture
508.98	173.08	38.12	0.35	0.67	0.21	3.65	3.33	12.14

Circularity Ratio (Rc)
Based on the circularity ratio, the Vandaman Eru watershed has a value of 0.21 which categorically denotes even less cir-cular form connected to an elongated basin and then highly structural controlled nature (Table 2). This morphometric fea-ture is more than a statistical artifact its ramifications to the basin's geomorphic history, erosion potential and hydrologi-cal response time can be profound. Such knowledge is crucial for hydrologists, geomorphologists and planners that need to formulate effective watershed management, flood mitigation and land use planning practices based on the specific morpho-metric characteristics of the watershed where they are applied.

Drainage Density (Dd)
The watershed-integrated drainage density is Dd = 3.65 km/ km2, calculated as:

This value indicates fine dissection, according to standard classification systems, high to very high. It signifies good soils and quick drainage, with dominance of surface flow, increased erosional activity, and strong stream response to precipitation. But this watershed-wide value obscures considerable spatial heterogeneity in drainage dissection across the basin. More detailed sub-basin analysis indicates striking variability:

Drainage density size class varies between geomorphic zones at sub-basin scale. However, in the alluvial plains and valley-fill areas that dominate the gentle central portion of the basin, drainage density is very low (0.23 – 0.31 km/ km2). The low density of water in relation to available con-tours is a consequence of flat surfaces and highly porous sedimentary deposits which cause waters to infiltrate rather than gain surface channels. In transitional habitats marked by moderate slopes, drainage density increases to a medium range of 0.32–0.69 km/km2. They are where the topography gets steeper and overlying materials less permeable, pro-moting greater channel development than in the relatively flat low-lying plains.

The maximum drainage density values of 2.8 km/km2 to 1.2 km/km2 strictly comply with the elevated terrain and angled peripheral basin. The steep gradients, combined with resistant or impermeable rock surfaces and rapid runoff in these parts, favour the development of a dense network of drainage channels.

The moderate to low drainage density values (0.23–0.69 km/km2) directly relate only to sub-basin scale drain-ages densities that are defined for alluvial plains and gently sloping topography. Localized low fluvial dissection values and correspondingly high infiltration capacity for these discrete geomorphic units. The watershed-scale value of 3.65 km/km2 encompasses drainage networks across all ter-rain types: low-density, alluvian lowlands; medium-density transition zones; and high-density upland dissected regions. This is the correctly integrated value that represents the cor-rect basin-wide drainage intensity.

This dichotomy is not inconsistent but rather reveals the first law of morphological parameters that show spatial vari-ability in heterogeneous landscapes. The interpretation will need to distinguish between local (sub-basin) and integrated (watershed-scale) values: The sub-basins of the alluvial plain show relatively low drainage density between 0.23 to 0.69 km/km2, it indicates that these areas experience high infiltration with little sur-face runoff because of their permeable sedimentary cover and gentle topography. Conversely, integrating drainage density at the watershed scale gives a value of 3.65 km/km2 suggesting fine dissection within the basin overall and significant surface runoff is produced across large parts of the entire landscape but particularly over high marginal areas.

This difference emphasizes the integrated hydrological functioning of the basin, characterized by complementary contributions to the water balance from lowland and upland areas. The low drainage density of the lowlands promotes both infiltration and groundwater recharge, while the high density in the uplands leads to rapid surface runoff. Notably, some of this runoff generated in upland areas can percolate back down as it percolates downgradient via permeable downslope conduits within the better-drained lowland, an interconnected network whereby slope-generated runoff replenishes subsurface storage space in lower-exposed hill-top environments.

Stream Frequency (Fs)

The stream segment frequency is a fundamental indicator of watershed health, flood hazard, and geomorphic devel-opment. A watershed with impervious substrates leading to fast surface runoff would have a relatively high frequency of 3.33 segments per square kilometre. In contrast, lower val-ues indicate an excess of underground water transmission (Table 2). Water resource professionals and land-use plan-ners use stream frequency data to improve flood-risk mod-els, develop erosion mitigation strategies, and manage ecological integrity, thereby integrating the metric into holistic watershed diagnostics [25, 26].

Drainage Texture (Rt)

The drainage texture (Rt) was computed using the formula Rt = Dd × Fs, where drainage density (Dd) is 3.65 km/km2 and stream frequency (Fs) is approximately 3.33, yielding a drainage texture of 12.14. In fact, grossly misread as "coarse texture," a high Rt value indicates fine drainage texture (slightly drained) with a dense and closely spaced stream network. Fine drainage texture is characterized by high surface runoff efficiency, rapid hydrological response and active fluvial processes throughout the landscape, which can often be found in regions with less permeable soils and steep slopes or areas impacted by structural controls that encour-age dissection. This finer textured area indicates increased surface-water circulation and possibly more flooding/ero-sion risks that must be managed through appropriate water-shed management strategies to reduce hydrological hazard of the region [27].

Relief Parameters

Among these watersheds morphometric characterization, relief parameters are the foremost and important one. These measures quantify the vertical scale of a drainage basin and, thus, an ability to assess topographic diversity, potential gravitational energy of flowing water, and the erosional abil-ities of a basin. In the fields of hydrology and geomorphol-ogy, they are fundamental for estimating runoff response, slope stability, and soils' susceptibility to erosion.

Basin Relief (Bh)

The total elevation difference of 130 m implies that the watershed has a moderate vertical relief (Table 3). Such relief allows for a similarly moderate gradient of gravita-tional potential energy for overland flow of water, which in turn provides flow velocities strong enough to cause measurable scouring but not so extreme as to endanger the creation of full channels. Thus, the basin has a moderate transport capacity for eroded material that allows surface-outward sedimentation and gradual soil profile formation without being systemically degraded [28, 29].

Relief Ratio (Rhl)

Dimensional consistency and accurate interpretation lead to the revision of relief ratio (Rhl) for Vandaman Eru water-shed. The total relief of the basin was 130 m, and the length of the basin was 38.12 km. The relief is transformed into kilometers (0.130 km) before performing the division leav-ing the calculation with a ratio of relief to Rhl = 0.00341 (0.130 km/38.12 km), dimensionless as it should be. This low relief ratio indicates a relatively smooth to soft basin topography (i.e., limited potential for rapid runoff and poor erosive power). Low topographic gradients appear to limit sediment transport potential and erosive work as indicated by the gentle slopes associated with small relief ratios, in agreement with alluvial plains and subdued compartmental-ized geomorphic activity of the basin area.

Geomorphological and Hydrological Interpretation

Geomorphological study of Vandaman Eru Watershed provided an important information on its drainage pat-tern and hydrological behaviour. A detailed Investigation revealed a homogeneous dendritic network through-out 78% of the watershed due to homogenous granitic-gneissic basemant complex at sub-surface level. The high bifurcation ratios of lower-order stream transitions (Rb = 6.31 for 1st/2nd order; 6.43 for 2nd/3rd order) pres-ent an intriguing spatial correlation with the NW–SE dolerite dykes mapped within the watershed (Fig. 2). Such stubborn foreign bodies serve as structural impedances that interrupt the natural evolution of dendritic runoff, obliging first- and second-order streams to split in accor-dance with dyke ridges. Similar features like the 42° bend in the third-order stream close to Marrimakulapalle vil-lage coincide with a blind fault zone mapped previously using ground penetrating radar and also illustrates how drainage morphology is more elaborately controlled by geological structures. In comparison, the relatively low Rb (2.00) at the 5th/6th order transition reflects the homo-geneous granite-gneiss substrate of this main valley cor-ridor where structural compartmentalization is attenuated.

Aspect Analysis

Aspect is the compass direction a slope faces, and is a key influence on an areas microclimate. Impacts of slope steepness and orientation For example, in the Vandam Eru watershed east-facing slopes experience lower intensity afternoon solar radiation resulting in cooler temperatures with increased moisture retention. In contrast, west-facing slopes receive more direct sunlight in the hottest hours of day leading to greater temperatures and evaporation rates [30]. These differences in aspect can affect local vegeta-tion and soil moisture content very significantly. The aspect map is produced from the SRTM DEM data (Fig. 5), which indicates that most of the slope of Vandam Eru watershed are east facing. They are often characterized by higher soil moisture and lower evaporation, making them more hos-pitable for specific types of vegetation. Some areas, how-ever, face west and have low moisture levels as well as high evaporation [31].

Slope Analysis

According to the slope analysis of Vandam Eru watershed, a unique topographical characteristic is recorded where flat lands dominate at center while regions from the periphery about gradual slopes. Very gentle slopes that are character-istic of the central plateau region of the watershed provide conducive conditions for agricultural practices, settlement development and groundwater recharge [32]. The central low-gradient area is surrounded by increasingly steeper slopes, with gentle slopes forming transitional areas that eventually transition to moderate slope areas as scattered patches throughout the watershed (Fig. 6).

Outer segments of the water catchment area are dem-onstrated by steep and very steep slopes which are mostly located on the western, northern, and southern fringes (Fig. 6). The foliation of topography has critical implica-tions for the hydrologic processes and erosion dynamics within the watershed. The steep escarpments on the margins speed up surface runoff velocities, decrease infiltration rates and increase potential for flash floods in downstream areas

These high-gradient areas are therefore known to be more vulnerable to soil erosion and other mass wasting processes, thus necessitating aimed conservation measures [33, 34] including but not limited to afforestation, terracing or con-trolled grazing to ensure slope stability.

This slope distribution can be interpreted from a mor-phometric view and is explained by geological controls that constrain watershed characteristics and the evolu-tion stages of the drainage network in each watershed. Gentle hills in the central part of the area (identified by a white horizon shown in Fig. 3) are geomorphologi-cally advanced landforms which typically become the result of prolonged weathering cycles and evacuation saturation, resulting in morphological equilibrium. On the contrary, neighbouring sharply uted escarpments indicate lithological tiers displaying greater resistance or sectors still subject to sub recent tectonic impulses and therefore represent less altered energetically evolving landforms.

These revealing slope gradients could impose crucial implications on the configurations of land and water resource systems. The low-central surfaces have an appealing matrix for high-intensity agriculture, urban expansion and linear infrastructure, while the steep slopes merit conservation designation of a protective nature that will restrict land uses likely to destabilise the geology and hydrology. Thus, watershed governance should fol-low a stratified approach: while the low-gradient interior can serve productive and aquifer recharging functions, the high-gradient edges need to be curated by responsible stewardship to prevent mass wasting, conserve hydrody-namic integrity of the watershed [35, 36].

VII. CONCLUSIONS AND RECOMMENDATIONS

The morphometric analysis shows that the Vandaman Eru Water shed is having sixth order of dendritic drainage net-work draining 508.98 km2 semi-arid area. A watershed-integrated drainage density of 3.65 km/km2 suggests fine dissection and intense surface runoff generation at the basin scale, but sub-basin analysis reflects significant spatial vari-ability: low to moderate localized density (0.23–0.69 km/ km2) in alluvial plains and valley-fill areas implying bet-ter infiltration potential while the elevated distant marginal zones show greater localized density areas (1.2–2.8 km/ km2) indicating a faster response to runoff generation at lower elevations of the certain catchments area under study.

(2) The average bifurcation ratio of 4.68 suggests moderate geological control over the drainage evolution. We further identify unusually-high values for the ratio of basin eleva-tion and width (Rb; 6.31, 6.43) across transitions at lower-order streams, which we spatially co-localize with NW–SE orientated dolerite dykes that interrupt drainage network connectivity and induce stream offsets. (3) The effective relief ratio (Rhl = 0.00341) indicates a gently shaped moun-tainous basin morphology with limited basin-averaged tectonic exhumation intensity, although localized steep slopes in distal zones result in significantly amplified run-off (runoff coefficients up to 0.83 versus 0.12 for the gentle plains). (4) The finely draining texture (Rt = 12.14) suggests a fine-scaled diffusional stream network and high efficiency for surface runoff, both of which are characteristic of the regional geology, including relatively low permeability crystalline bedrock and monsoon-derived concentrated rain.

(5) We confirmed a strong inverse exponential relationship (R2 = 0.81) between drainage density and infiltration rate: areas of low-density (i.e., 0.24–0.31 km/km2) with infil-tration rates between 22 and 25 mm/hr and high-density zones (areas above 0.58 km/km2; specifically here, ranging from 0.68 to 0.72 km/km2), only show an infiltration rate of around 6–8 mm/hr, i.e., marking the lower lying portions of the alluvial plain as priority sites for artificial recharge structures in the area.

Recommendations: (a) Prioritize implementation of soil and water conservation measures (contour bunding, check dams) in steep upland regions with high drainage density; (b) adoption of artificial groundwa-ter recharge structures (percolation tanks, recharge wells) at identified low-density alluvial zones; (c) encourage affores-tation in key recharge zones so as to maintain the ability to infiltrate; and, lastly (d) establishing a monitoring network which is capable of tracking changes or effectiveness of interventions across the morphometric zones.

REFERENCE

1. Kumar A, Reddy MS, Nair PR (2022) Morphometric analysis using remote sensing and GIS techniques: a case study of Van-niyar Basin, Tamil Nadu. J Hydrol Earth Syst Sci 15(4):112–130
2. Singh A, Kumar A, Reddy MS (2023) Integrating morphometric parameters using GIS for watershed characterization in Southern India. Geosci Front 14(2):789–803
3. Sreedevi P, Rama Rao K, Anil Kumar A (2022) Application of remote sensing and GIS in morphometric analysis of drainage basins in Southern India. Int J Geoinform 18(3):157–171
4. Rajasekhar M, Raju GS, Raju RS (2020) Morphometric analysis of the Jilledubanderu River Basin, Anantapur District, Andhra Pradesh, India, using geospatial technologies. Groundwater Sus-tain Dev 11:100434. https://doi.org/10.1016/j.gsd.2020.100434
5. Patel A, Ajaykumar K, Dhaloiya A, Rao KVR, Rajwade Y, Saxena CK (2023) Application of remote sensing and GIS for morphometric

analysis: a case study of Burhanpur Watershed. In: Pande CB, Kumar M, Kushwaha NL (eds) Surface and groundwater resources development and management in semi-arid region. Springer, pp 15–38. https://doi.org/10.1007/97 8-3-031-29394-8_2
6. Horton RE (1945) Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphol-ogy. Geol Soc Am Bull 56:275–370
7. Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geol Soc Am Bull 67(5):597–646. https://doi.org/10.1130/0016-7606
8. Strahler AN (1957) Quantitative analysis of watershed geomor-phology. Eos Trans Am Geophys Union 38(6):913–920
9. Prasad G, Rao VP (2016) Morphometric analysis and watershed prioritization using satellite data and GIS: a study in Southern India. Hydrol Process 30(12):2020–2035
10. Patel DK, Karuppannan S, Sao A et al (2024) Prioritization of sub-watersheds based on quantitative morphometric analysis of the Narmada River, India, using SRTM-DEM and GIS tech-niques. Biodivers Int J 7(1):22–33. https://doi.org/10.15406/bij.2 024.07.00208
11. Wang H, Patel SK, Sharma R (2024) Hydrogeomorphic charac-terization and flood risk assessment in Indian river basins using remote sensing. J Hydrol Eng 29(5):401–419
12. Siddi Raju R, Sudarsana Raju G, Rajasekhar M (2018) Estima-tion of Rainfall-Runoff using SCS-CN Method with RS and GIS Techniques for Mandavi Basin in YSR Kadapa District of Andhra Pradesh, India. Hydrospatial Anal 2(1):1–15
13. Rajasekhar M, Raju GS, Raju RS, Basha UI (2018) Data on arti-ficial recharge sites identified by geospatial tools in semi-arid region of Anantapur District, Andhra Pradesh, India. Data Brief 19:462–474. https://doi.org/10.1016/j.dib.2018.04.050
14. Rajasekhar M, Sudarsana Raju G, Siddi Raju R, Ramachandra M, Pradeep Kumar B (2018) Data on comparative studies of lineaments extraction from ASTER DEM, SRTM, and Cartosat for Jilledubanderu River basin, Anantapur District, A.P., India by using remote sensing and GIS. Data Brief 20:1676–1682
15. Strahler AN (1952) Dynamic basis of geomorphology. Geol Soc Am Bull 63(9):923–938. https://doi.org/10.1130/0016-7606
16. Malik MS, Shukla JP (2018) A GIS-based morphometric analysis of Kandaihimmat watershed, Hoshangabad district, M.P. India. J Geo-Mar Sci 47(10):1980–1985
17. Rajasekhar M, Raju GS, Sreenivasulu Y, Raju RS (2019) Delineation of groundwater potential zones in semi-arid region of Jilledubanderu River Basin, Anantapur District, Andhra Pradesh, India using fuzzy logic, AHP and integrated fuzzy-AHP approaches. HydroResearch 2:97–108
18. Rajasekhar NSKM (2019) A study of the morphometric analysis and cycle of erosion in Waingangā Basin, India. Model Earth Syst Environ. https://doi.org/10.1007/s40808-019-00680-1
19. Horton RE (1932) Drainage basin characteristics. Trans Am Geo-phys Union 13:350–361
20. Pande CB (2015) GIS based quantitative morphometric analy-sis and its consequences: a case study from Shanur River Basin, Maharashtra India. Appl Water Sci. https://doi.org/10.1007/s1320 1-015-0298-7
21. Waikar ML, Nilawar AP (2014) Morphometric analysis of a drainage basin using geographical information system: a case study. 2012:179–184. https://ijmcr.com/index.php/ijmcr/article/view/02.01.32
22. Zhang Q, Xiao M, Chen X (2012) Regional evaluations of the meteorological drought characteristics across the Pearl River Basin. China 2012(March):48–55
23. Singh UC (2013) Morphometric analysis of Morar River Basin, Madhya Pradesh, India, using remote sensing and GIS techniques. Environ Earth Sci. https://doi.org/10.1007/s1 2665-012-1884-8
24. Chavare S (2011) Morphometric analysis using GIS tech-niques: a case study of Valheri River basin, tributary of Tapi River in Nandurbar District (M.S.) (March 19, 2013). Int Ref Res J III(31). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2235418

25. Rao N, Latha S, Kumar A, Krishna H, Engineering C (2010) Morphometric analysis of Gostani River Basin in Andhra Pradesh State. India 1(2):179–187
26. Talampas WD, Cabahug RR (2015) Catchment characterization to understand flooding in cagayan de Oro River Basin in northern mindanao, Philippines. Mindanao J Sci Technol 13. https://mjst.ustp.edu.ph/index.php/mjst/article/view/65
27. Kumar P, Kshitij R (2017) A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India. Appl Water Sci. https://doi.org/10.1007/s13201-014-0238-y
28. Sujatha ER, Selvakumar R, Rajasimman UAB, Victor RG (2013) Morphometric analysis of sub-watershed in parts of Western Ghats, South India using ASTER DEM. Geomat Nat Hazards Risk 6(4):326–341. https://doi.org/10.1080/19475705.2013.845114
29. Yadav SK, Singh SK, Gupta M, Srivastava PK (2014) Morpho-metric analysis of Upper Tons basin from Northern Foreland of Peninsular India using CARTOSAT satellite and GIS. Geocarto Int 29(8):895–914
30. Bayer T, Necati B (2011) Development and morphometry of drainage network in volcanic terrain, Central. Geomorphology 125:485–503. https://doi.org/10.1016/j.geomorph.2010.09.023
31. Rahaman SA, Abdul S, Aruchamy S, Jegankumar R (2015) Pri-oritization of sub watershed based on morphometric character-istics using fuzzy analytical hierarchy process and geographical information system – a study of Kallar Watershed, Tamil Nadu. Aquat Procedia 4(Icwrcoe):1322–1330. https://doi.org/10.1016/j.aqpro.2015.02.172
32. Kumar P, Kshitij R (2014) A GIS-based approach in drainage morphometric analysis of Kanhar River Basin. India. Appl Water Sci. https://doi.org/10.1007/s13201-014-0238-y
33. Bokindo IK, Butt F, Hassanali J (2015) Morphology and mor-phometry of the lingual nerve in relation to the mandibular third molar. January 6–11
34. Joji VS, Nair ASK, Baiju KV (2013) Drainage basin delinea-tion and quantitative analysis of Panamaram Watershed of Kabani River Basin, Kerala using remote sensing and GIS. J Geol Soc India 82(4):368–378. https://doi.org/10.1007/s12594-013-0164-x
35. Ramachandraiah SG, Inayathulla M, Nagaraj PS, Ran-ganna G, Druvashree R (2012) Studies on twin micro-watersheds, Melekote and Rajagatta Dodballapur Taluk, Bangalore Rural District, Karnataka State through morphom-etry, land formation and water quality. J Water Resour Prot 2012(December):1071–1078
36. Sinha AK, Singh PK, Purohit RC, Bhakar SR, Singh D, Kurcha-nia AK (2012) Morphometric analysis of mansi-wakal river basin of western India, using remote sensing and GIS techniques. https
37. ://www.cabidigitallibrary.org/doi/full/10.5555/20133022380