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SPATIAL VARIATIONS OF TECTONIC QUIESCENCE AND RESURGENCE CONSTRAINTS FROM THE LONGITUDINAL PROFILES AND CONFLUENCE ANGLES OF THE CAUVERY RIVER BASIN

AL Fathima[1*], Mu. Ramkumar[1], V. Thirukumaran[2], Athira Pramod[1] and Juni K.J[1]

[1] Department of Geology, Periyar University, Salem-11, India
[2] Department of Geology, Government Arts College (Autonomous), Salem-7, India

Corresponding Author Mail ID: alfathima28@gmail.com

Abstract

Cauvery River, an east-flowing river, originates at about 1345 m elevation in the Western Ghats hill ranges in the southern part of the Indian Peninsula. The study focused on geomorphic aspects of this river by examining longitudinal profiles, knickpoints and confluence angles to understand the interactions between geology, tectonics, and fluvial processes in shaping river landscapes. Cauvery and tributaries display uneven longitudinal profiles with numerous knickpoints along the profiles. High R^2 values in longitudinal profiles indicate a strong correlation between stream slope and distance, suggesting equilibrium conditions and consistent erosional processes. Conversely, variability in R^2 values highlights the dynamic nature of these systems. Field investigations were conducted at selected knickpoints and knickzones to validate the extracted data. Each sub-basin within the Cauvery Basin exhibits unique topographic and geomorphic characteristics, reflecting diverse geological settings and regional influences. The study emphasizes the distinctiveness of sub-basins such as Hemavathi, Shimsha, Arkavati, and Kabini, highlighting their varied dynamics. The presence of knickpoints, especially at lithologic boundaries and structural features underscores the influence of geological factors such as erosion, base-level fluctuations, and tectonic activities. Associations between factors and abrupt changes in elevation along river profiles illustrate the complex interplay between geological processes and fluvial geomorphology, underscoring the multidimensional nature of landscape evolution. This research contributes to understanding neotectonic activity and its impact on river morphology, providing insights into the intricate interactions between geological processes and fluvial dynamics in the Cauvery River Basin.

Keywords: Cauvery River Basin; Confluence angle; Knickpoints; Longitudinal profile; Tectonic activity

Introduction

The drainage system within a region serves as a chronicle of tectonic transformations (Schumm, 1986). Tectonic activities alter stream flow characteristics primarily by reshaping the base level of erosion, adjusting incision rates, or inducing diversions. Analysing stream features can unveil the tectonic disturbances responsible for incisions, provided there hasn't been a diversion forced by tectonic activity (Larue, 2008a). Erosion rates across landscapes are believed to be influenced by tectonic uplift. Thus, deriving erosion rate indicators from topographic data offers innovative avenues for pinpointing areas of tectonic movement (e.g., Wobus et al., 2006a) and may even reveal potentially active faults (e.g., Kirby and Whipple, 2012). The analysis of channel networks holds particular significance in discerning external influences from the topographic configuration, as fluvial networks establish boundary conditions for adjacent hillslopes, thereby serving as conduits for transmitting climatic and tectonic cues throughout the landscape (e.g., Burbank et al., 1996).

Longitudinal profiles of channels arise from a complex interplay involving fluvial incision, lithological characteristics, tectonic forces, and shifts in base-level conditions (Larue, 2008b). The evolution of these profiles is heavily influenced by lithological diversity and by analysing the river profile's geometry, one can spatially identify patterns of rock uplift. Notably, the presence of knickpoints, where river gradients abruptly change, signifies ongoing tectonic processes. River profiles in equilibrium typically exhibit a concave upward shape, indicating a balance between fluvial incision and base-level changes (Keller and Pinter, 2002). Conversely, if fluvial incision outpaces base-level changes, a smooth downstream concavity develops (Larue, 2008b), attributed to increased discharge and reduced grain size. Convex profiles suggest higher uplifting rates relative to denudation. Knickpoints, often caused by resistant lithology or increased shear stress, denote stream disequilibrium and signal adjustments in base level (Bishop et al., 2005; Larue, 2008b). Additionally, lateral tilting and vertical tectonic movements contribute to profile anomalies, offering insights into the tectonic history of a drainage basin. Thus, longitudinal profiles serve as valuable indicators of a basin's tectonic evolution.

Understanding the impact of tectonic forces on the evolution of channel networks and longitudinal profiles is crucial for identifying and analysing neotectonic activity. The dynamic interplay between fluvial processes, lithological variations, and tectonic influences shapes the morphology of river channels over time. However, despite significant advancements in our understanding of these processes, there remains a need to accurately distinguish between tectonically induced changes and those driven by other factors such as climatic variations. Moreover, the identification of key indicators, such as knickpoints and profile anomalies, can provide valuable insights into the extent and nature of tectonic movements within a drainage basin. Therefore, the development of robust methodologies and analytical frameworks that leverage channel morphology data to detect and characterize neotectonic activity is essential for advancing our understanding of landscape evolution and terrain stability in tectonically active regions. The primary objectives of the present study entail characterizing neotectonic activity and examining the fluvial response to terrain stability within the Cauvery River Basin. This will be achieved through a comprehensive quantitative analysis of longitudinal profiles, coupled with an investigation into the influence of confluence angles of tributaries on the main river channel.

Geological Setting

The Cauvery River is one of the perennial rivers of south India draining over the states of Karnataka, Kerala and Tamil Nadu and its catchment lies between 10°7'N and 13°28'N, 75°28'E and 79°52'E. Cauvery River Basin trends NW-SE in direction and has an areal extent of 81155 sq. km. and a delta of 8800 sq. km. The tributaries are Amaravati, Arkavati, Bhavani, Shimsha, Thirumanimutharu, Thoppaiyaru, Sarabanga, Chinnar, Palar, Suvarnavati, Lakshmantirtha, Hemavati, Kaveri, Kabini, Kudamarutti, Aiyaru, Noyyal and distributatries are Arasalar, Coleroon, Kaveri, Vettar, Vennar. The river Cauvery originates from the Talakavery at the Brahmagiri hills of Western Ghats, the river has a total length of 760 km. A major part of the catchment zone lies in Karnataka state. The Cauvery Basin is peninsular India's fifth-largest drainage area (Kale et al. 2014).

The Delta head of this river is located at Mukkombu, Tiruchirapalli, from where the river branches off into the Cauvery and Coleroon. At Kallanai (Grand Anicut—Tiruchirappalli), it further branches off into two distributary channels, namely, the Cauvery and the Vennar. They branch further into 36 channels, whose total length is 1,607 km. These in turn branch off into 2,988 channels running to a length of 18,395 km (Kandaswamy 1986).

The mean annual temperature of the Cauvery River Basin is 25° C, however, in summer the maximum temperature reaches up to 43°C. The average rainfall of the basin is 110 cm, which has an average elevation of about 630 m. The Southwest monsoon is responsible for the rain in the basin, 75% of the annual rainfall, 85% of the annual sediment transport and 73% of annual water discharge acquired for the three months (June- August) (Vaithiyanathan et al., 1992; Sharma and Rajamani, 2001). Figure 1 shows the map of the location study area prepared in ArcGIS software.

The river originates in the Brahamagiri Range of the Western Ghats at an elevation of 1345 m above mean sea level and extends approximately 800 kilometers to the Bay of Bengal. The river's initial route is eastward through the Mysore Plateau (average elevation 1000 m). The river's eventual course in the state of Tamil Nadu, where it has created flood plains and a delta, is also eastward. A series of block mountains lie between the Mysore Plateau and the Tamil Nadu lowlands, believed to have been created after the Indian and Asian continents collided (Radhakrishna 1993). The river's drainage pattern becomes trellis-like in this steep section, resulting in an overall southern flow for the main channel. According to Radhakrishna (1993), the river in the Mysore Plateau has been revitalized by the region's uplift. Two important streams, the Bhavani and Amravati, enter the Cauvery River in its lower reaches in the south. The raised sections of the Nilgiri, Cardamom and Anaimalai hills also feed these two important tributaries. The Palghat–Kaveri gap, which separates two continental blocks, is assumed to be followed by the two major tributaries and the main canal (Radhakrishna 1993).

The Cauvery River Basin is dominated by Archean (>2500 Ma) gneissic, charnockitic, and granitic rocks (Figure 2). The region is separated into two major terranes:

the Dharwar Craton in the north and the granulite terrane in the south. The two terranes are separated by a transition zone to the north, where granitic rocks with supracrustal belts (schist belts) are metamorphosed to grades lower than the amphibolite facies. Both granitic and supracrustal rocks transform to granulite grade south of the transition zone, resulting in charnockite, pyroxene granulite, and high-grade amphibolite assemblages. The higher reaches' transition zone gneisses and charnockites have been dated to be between 3000 and 2500 Ma. (Friend and Nutman, 1991). The craton-southern granulitic belt boundary has been well-defined as a zone of strong faulting and thrusting in which the charnockite terrane has been raised and overthrusted onto the craton (Radhakrishna, 1968). The Himalayan orogeny, according to Radhakrishna (1993), caused the uplift and construction of many block mountains by reactivating the shear and fault systems (Sharma and Rajamani, 2001).

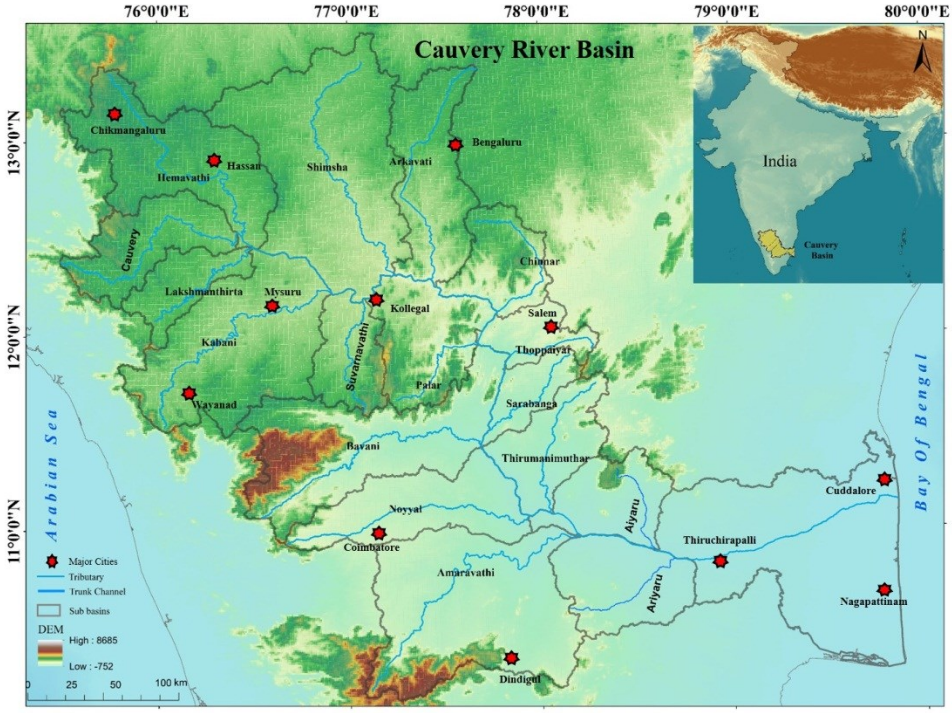

Figure 1: Cauvery River Basin shows the location of the study area. The inset map shows the location of the Cauvery Basin in India. SRTM DEM is downloaded from USGS Earth Explorer (https://earthexplorer.usgs.gov/).

Materials and Methods

Documentation and Analysis of Longitudinal Profile

Google Earth Pro, provides a user-friendly interface that allows researchers to easily access and visualize elevation data and is a widely utilized tool for observing our planet. The software primarily used the Shuttle Radar Topography Mission (SRTM) dataset for its elevation data, which has a resolution of 30 meters. Various features within Google

Earth contribute to the advancement of geomorphological concepts. The platform allows users to tilt scenes and view landscapes in three dimensions, enabling enhanced visualization. Additionally, functionalities such as measurement tools and elevation profile construction greatly aid in the identification and characterization of landscapes (Dolliver, 2012). The simplicity of accessing data through Google Earth Pro may outweigh the potential benefits from other datasets that require more technical expertise to acquire and process.

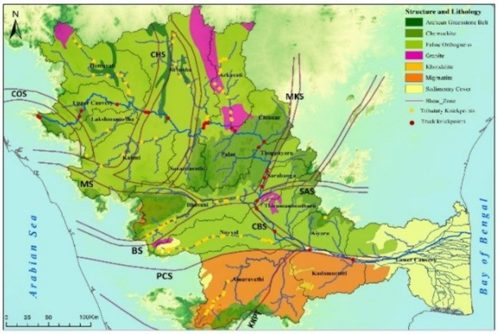

Figure 2: Shows the lithology and structure of the Cauvery River Basin (Geological Survey of India Map), drainage (source: mapped from toposheets from SOI https://www.surveyofindia.gov.in/). Figure 3: The knickpoint distribution along the trunk river and immediate tributaries with the major faults of the Cauvery River Basin (source: lineaments from atlas of Geological Survey of India), SRTM DEM (source: https://earthexplorer.usgs.gov/).

To generate the longitudinal profile of the Cauvery River and tributaries first, the main channel and tributaries are digitized in Google Earth Pro. Later, elevation values at an interval of 1 kilometre were entered in Excell from the elevation profile provided in Google Earth Pro. The distortion of data due to the vegetation cover is avoided by the use of multi-temporal satellite images available in the software. Longitudinal profiles were made in Excell with distance in meters as x-axis values and elevation in meters as y-axis values. The convex reaches or sudden falls in the longitudinal profile are marked and verified again in Google Earth Pro. These locations are saved and extracted as *kml* file format followed by the ground truth verification of the work with field survey. In this study, we conducted a longitudinal profiles analysis of the channels of 16 main tributary rivers and the trunk channel within the Cauvery Basin. Comprehensive observations were made along each river channel, spanning from their respective origins to their confluences. Anomalous points were identified through the detection of flow patterns contrary to the prevailing slope conditions.

The metric known as "Goodness of Fitness" (R^2) serves as a crucial indicator of a drainage basin's level of maturity. During a phase of equilibrium in the stream, the slope typically exhibits a linear relationship, reflected by a high R^2 value in the concave longitudinal profile, particularly evident in the primary stream profile of the basin (Ramkumar 2019). However, the dynamic interplay between intrinsic and extrinsic factors can cause the longitudinal profile's knickpoint to shift from downstream to upstream as a transient response. This phenomenon disrupts the linear fit observed in the slope-area profile, leading to a decrease in the R2 value, particularly noticeable in the primary stream's longitudinal profile within the basin. In longitudinal profile analysis of rivers, the R-squared (R^2) value is calculated using excel. The collected data is organized into pairs of values, typically representing distance along the river's course (independent variable, x) and corresponding stream slope (dependent variable, y). A linear regression model is fitted to the data. This model aims to find the best-fitting line that describes the relationship between distance and stream slope. The equation of the line is typically of the form y = mx + b, where m is the slope of the line (which represents the rate of change of stream slope with distance) and b is the y-intercept. n longitudinal profile analysis, R^2 is significant because it provides a quantitative measure of how well the linear model represents the relationship between variables along the stream's course.

A high R^2 value indicates that the linear model fits the data well, suggesting a strong correlation between stream slope and distance. This implies that the stream is likely in an equilibrium state, with consistent erosion and sediment transport processes along its course. Conversely, a low R^2 value suggests that the linear model does not fit the data well, indicating variability or non-linearity in the relationship between stream slope and distance. This variability could be due to factors such as changes in geological substrate, tectonic activity, or human disturbances (Leopold et, al., 1964) The longitudinal profile graph slope, expressed as mx + b of a river channel is significant in terms of landscape and channel evolution for several reasons. The gradient (m) of the longitudinal profile represents the rate of change of elevation (or slope) with respect to distance along the river's course. A steeper gradient indicates a faster rate of descent, which typically corresponds to areas of rapid erosion, such as waterfalls or steep rapids. In terms of landscape evolution, steep gradients suggest active erosion and rapid channel incision, which can shape the overall landscape over time.

The y-intercept (b) of the longitudinal profile represents the elevation of the river channel at a specific reference point along its course. This point may correspond to the source of the river, where it originates from higher elevations, or to a base level, such as a lake or the ocean, where the river eventually flows into. The y-intercept provides important information about the overall elevation profile of the river and its relationship to the surrounding topography. Changes in the slope (m) and y-intercept (b) of the longitudinal profile over time reflect the evolutionary trajectory of the river channel. For example, a decrease in slope may indicate a decrease in the rate of erosion or sediment transport, possibly due to changes in discharge, substrate, or tectonic activity. Conversely, an increase in slope may suggest rejuvenation of the river channel, often associated with increased erosional activity and channel incision. Longitudinal profile slope can also indicate the response of the river channel to tectonic uplift, climate change, or other external forces. For instance, a steepening of the slope may result from tectonic uplift, which increases the river's erosive power and leads to greater incision. Similarly, changes in slope and y-intercept can reflect variations in climate, such as increased precipitation leading to higher discharge and more rapid erosion (Montgomery and Buffington, 1997; Howard, 1994).

Identification of Confluence Angle

To find out the actual angle theta between the mainstream and tributaries at the confluences, we have used a graphical technique adopted from Mosley's momentum equation (Figure 4) with the help of Google Earth Maps and the digitized stream networks. The streams were digitized using the Survey of India toposheets of 1:50000 scale. 154 topographic maps were downloaded from the SOI website (https://www.surveyofindia.gov.in/) and the images were geometrically rectified with respect to the WGS 1984 data frame. The drainages were digitized using the ArcGIS 10.8 software for morphometric analysis. The channel segments have been ranked according to Strahler's (1964) stream ordering system. The technique for angle measurement of each confluence is, a straight line has been drawn from each confluence between the tributary and main upstream which is parallel to the main downstream towards the reverse of the flow direction, considering an acute angle with respect to the main downstream. The confluence angles of tributaries are shown in Figures 10 and 11.

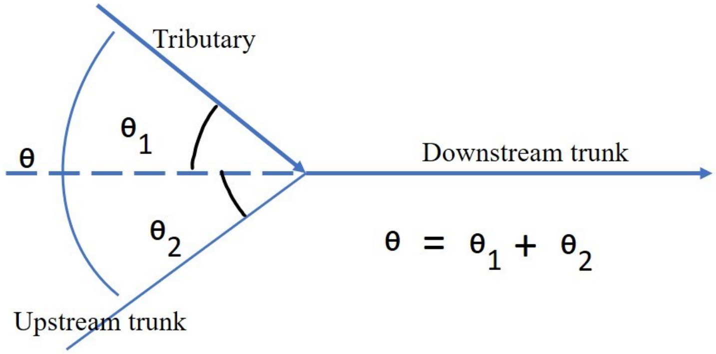

Figure 4: Sketch for confluence angle measurement (After Mosley 1976)

Results

Knickpoints recorded in the longitudinal profiles of the Cauvery River (Figure 5) and its 16 tributaries (Figure 6). The comparison profile of all tributaries is also shown in Figure 9. The 760-km-long Cauvery River shows convex and concave shapes upstream and downstream, respectively, and has an R2 (goodness of fit) value of 0.9345. These changes in stream profile shapes are separated by eight major knickpoints. However, there are several other minor knickpoints and knickzones along the river's course.

The longitudinal profile of Hemavathi has an R^2 value of 0.9682, 11 knickpoints in the downstream course and an average slope of y = -1.2729x + 997.57 (Figure 6a). The river confluences to the trunk river at an angle of 70^o (Figure 10a). Shimsha has an R^2 value of 0.8871, has 8 knickpoints in the downstream course and an average slope of y = -

1.4307x + 822.08 (Figure 6b). The river confluences to the trunk river at an angle of 50° (Figure 10b). The R^2 value of Arkavathi is 0.9013, has 7 knickpoints in the downstream course and an average slope of y = - 2.8092x + 975.3 (Figure 6c). The river confluences to the trunk river at an angle of 85° (Figure 10c). The longitudinal profile of Kabini has an R^2 value of 0.9475, has 4 knickpoints in the downstream course and an average slope of y = - 0.44x + 733.03 (Figure 6d). The river confluences to the trunk river at an angle of 50° (Figure 10e). Lakshmantirtha has an R^2 value of 0.9598 and has only 3 knickpoints, one in the catchment region in Wayanad district, Kerala and the river has an average slope of y = - 0.4837x + 810.63 (Figure 6e). The river confluences to the trunk river at an angle of 50° (Figure 10d).

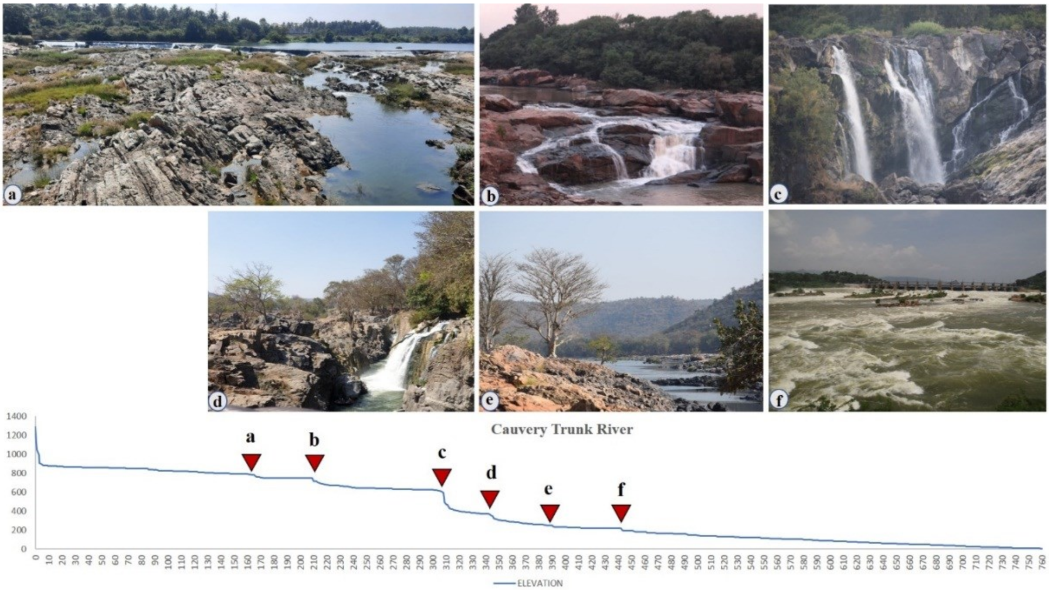

Figure 5: Knickpoints recorded in the longitudinal profiles of the Cauvery River. (a) step fault controlled waterfall in the upstream, which is the first prominent knickpoint along the course of the Cauvery River showing the bedrock channel (b) Chunchunakate falls, which is a fault-controlled knickpoint, (c) Barachukki Falls in the Sivanasamudra Falls which is the highest magnitude of knickpoint along the Cauvery, (d) Hogenekkal falls, NE-SW fault controlled major knickpoint, (e) knickzones and bedrock channel in the downstream of Hogenekkal, (f) Downstream of Mettur Stanley reservoir which is the anthropogenically altered major knickpoint in the Middle Cauvery River Basin

Suvarnavati has an R^2 value of 0.6284, has only 2 knickpoints in the catchment and the river has an average slope of y = -3.136x + 828.75 (Figure 6f). The river confluences to the trunk river at an angle of 75° (Figure 10f). The R^2 value of Chinnar is 0.8725, has 5 knickpoints in the course and the river has an average slope of y = -4.3053x + 414.06 (Figure 6g). The river confluences to the trunk river at an angle of 90° (Figure 11b). The longitudinal profile of Palar has an R^2 value of 0.9763, has only a knickpoint in the catchment and the river has an average slope of y = -6.5071x + 718.64 (Figure 6h). The river confluences to the trunk river at an angle of 125° (Figure 10h). The longitudinal profile of Bhavani has an R^2 value of 0.8648, has 12 knickpoints in the downstream course and the river has an average slope of y = -1.8192x + 473.69 (Figure 6i). The river confluences to the trunk river at an angle of 85° (Figure 11a). Thoppaiyaru has an R^2 value of 0.753, has six knickpoints in the downstream course and the river has an average slope of y = - 5.2861x + 549.29 (Figure 6j).

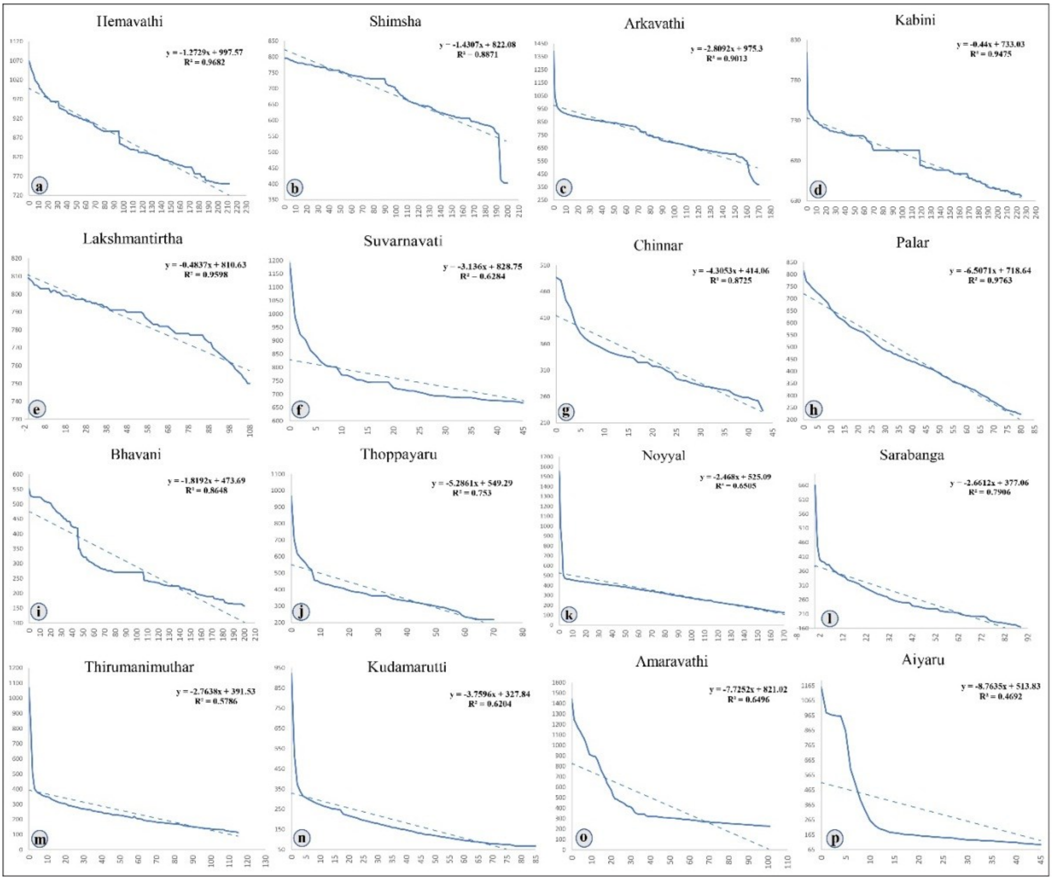

Figure 6: Longitudinal profiles of (a) Hemavati with subsequent breaks in the profile, (b) convex-up profile of Shimsha, (c) Arkavati shows concave-convex-concave nature, (d) Kabini shows prominent successive breaks in the profile, (e) convex-up nature in Lakshmantirtha, (f) concave profile in Suvarnavati, (g) concave profile of Chinnar, (h) Palar shows a highest slope of 9.763 with steep channel gradient, (i) Bhavani shows highly concave nature followed by a sudden fall in the course, (j) Thoppaiyaru, (k) Noyyal, (l) Sarabanga, (m) Thirumanimuthar, (n) Kudamarutti showing gradual slope in the channel (o) Amaravati shows steep slope followed by the gradual course in the channel (p) Aiyaru has the lowest slope/R^2 value and have a significant knickpoint in its upstream.

Figure 7: (a) Thoovanam waterfalls in Amaravati River Basin, is a prominent knickpoint, (b) knickzone in bedrock channel of Amaravati, (c) cobble-boulder deposited at the upstream courses of Amaravati, (d) channel flowing in knickzones of Arkavati River, also shows uplifted rocks in the right bank of the river, (e) Chunchi falls, which is highest magnitude knickpoint/knickzone in the in the downstream of Arkavati and flows into the narrow gorges in the Biligirirangan terrain, (f) pothole development in the riffle and chute structure in the downstream of Kodiveri waterfalls of Bhavani River, (g) gradual elevation difference in the knickzone in the Bhavani River shows the deposition of cobbles in the bedrock channel bed, (h) channel shows low energy condition in Noyyal River, (i) remnants of riffle and chute structure in the anthropogenically altered knickpoint in the Hemavati (j) Iruppu waterfalls in the upstream of Lakshmantirtha, which is the highest knickpoint in the upstream, (k) pebble deposited channel bed in the Kabini, (k) knickzone in the upstream of Hemavati River shows steep channel gradient, (l) gentle channel gradient in Bhavani, boundary hills of Bhavani sub-basin is also visible in the backdrop, (m) gradual and gentle downstream course of channel in Thirumanimuthar

Figure 8: (a & b) Knickpoint in the Sarabanga River shows bedrock channel with minor vertical drops in the course of the channel, (c) Agayagangai Falls, single and prominent knickpoint in the Aiyaru River (d) rocky channel bed along the knickzone in Shimsha with no sediment deposition indicating steep slope and high energy of the river, (e) boundary hill and bedrock channel in the vicinity of knickzone in Palar River, boundary hills of the sub-basin can be seen at the backdrop, (f) knickzone and the bedrock channel with sand deposition in the Palar River, (g & h) knickpoint and knickzones at Thirumanimuthar River, (i) Anaimadavu waterfalls at the upstream of Toppaiyaru River, (j) downstream flow of Aiyaru with no significant changes in the channel gradient, altered banks are also visible, (k) bedrock channel at the downstream of knickpoint in the Thoppaiyaru River, (l) minor knickpoint in the Hemavathi River in the bedrock channel, (m) knickpoint at the Suvarnavati River (Suvarnavati Dam), (n & o) shear zone and knickzone development in the Chinnar River.

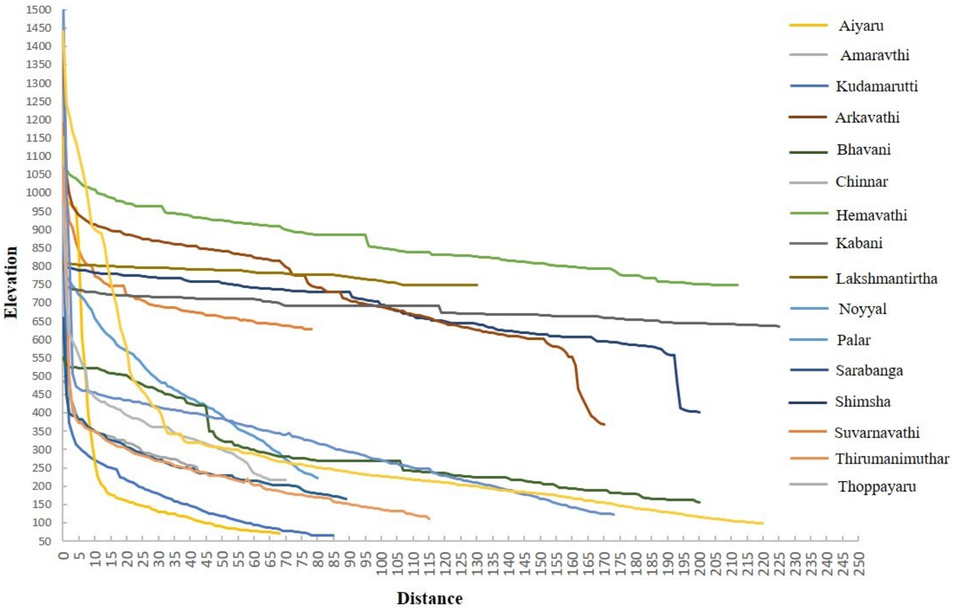

Figure 9: Comparison profile with the result of plots of longitudinal profiles of 16 tributaries of the Cauvery River, Hemavathi flows in an elevated terrain compared to the other tributary rivers in the basin, where Noyyal and Kudamarutti have the lowest base level.

The river confluences parallel to the trunk river at 180° (Figure 10g). The R2 value of the longitudinal profile of Noyyal is 0.6505, there are 12 knickpoints in the course, and the river has an average slope of y = -2.468x + 525.09 (Figure 6k). The river confluences to the trunk river at an angle of 50° (Figure 10h). The R^2 value of Sarabanga is 0.7906, has 9 knickpoints in the course and the river has an average slope of y = -2.6612x + 377.06 (Figure 6l). The river confluences with the trunk river at an angle of 35° (Figure 11g). Thirumanimuthar has an R^2 value of 0.5786, has 8 knickpoints in its course and the river has an average slope of y = -2.7638x + 391.53 (Figure 6m). The river confluences to the trunk river at an angle of 60° (Figure 11c). The R2 value of the longitudinal profile of Kudamarutti is 0.6204, there is only 1 knickpoint in the catchment, and the river has an average slope of y = -3.7596x + 327.84 (Figure 6n). The river confluences with the trunk river at an angle of 65° (Figure 11d). The R2 value of Amaravathi is 0.6496, there are nine knickpoints in the downstream course, and the river has an average slope of y = -7.7252x + 821.02 (Figure 6o). The river confluences with the trunk river at an angle of 65° (Figure 11e). Kudamarutti has an R^2 value of 0.4692 and has only 1 knickpoint in the catchment, which is Agayagangai Falls located in Kolli hills and the river has an average slope of y = -8.7635x + 513.83 (Figure 6p). The river confluences to the trunk river at an angle of 45° (Figure 11f).

Discussion

Behavioural Patterns of Major Sub-basins

The behavioural patterns of sub-basins within the Cauvery River Basin have been comprehensively investigated through extensive field surveys. The inclusion of selected field photographs in Figures 7 and 8 enriches the understanding of these patterns.

Hemavathi's catchment exhibits highly undulating topography with lateritic soil. Additionally, the Basin features a pediment-pediplain complex characterized by red soil. Knickpoints located upstream manifest within an incised channel with bedrock rapids, while flood plains commence in the upstream course itself. The Basin's geomorphology is significantly influenced by regional structural controls, evidenced by the N-S trending strike directions of bedrock reflections (Figure 8l). Downstream, well-developed terraces with pebbles and cobbles on old terraces and fine to medium sand on recent terraces are observed. Knickpoints are accompanied by observations of Mylonites, indicating a shear zone. Mid-channel bars, spanning 170 kilometers, exhibit flourishing vegetation cover, with the channel assuming meandering patterns downstream. Flood plain formation followed by natural levees becomes noticeable. As the channel progresses towards the confluence, a shift in channel morphology, characterized by riffle-chute structures and pebble gravel deposition, signifies active channel dynamics influenced by regional tectonics (Figure 7i).

Shimsha originates and traverses low-relief surfaces devoid of undulations, with ferrous/red soil dominating the Pedi plain amidst dense plantations. Despite this, the channel generates flood plains upstream and exhibits sand deposition within the channel bed. Structural controls become prominent as the channel nears the confluence, marked by Shimsha Falls, a major 76-meter cascade. Notably, the bedrock channel features a prominent N-S trending strike direction (Figure 8d). Downstream reactivation occurs approximately 130 kilometers from the source, characterized by increased velocity and riffle-chute structures in the channel bed (Figure 8d). Subsequent channel downcutting leaves paleo-terraces on either bank, ultimately leading to the channel's descent into deep gorges en route to its confluence.

Arkavati encounters numerous structural control points, or knickpoints, as it progresses downstream. The initial knickpoint, situated 68 kilometres from the channel's origin, occurs within an incised channel bed comprised of granitic gneiss (Figure 7d). Erosive activity results in the absence of material deposition such as gravel and sand downstream. This erosional signature persists throughout the Basin's knickpoints. Near the downstream region, boundary hills shape an L-shaped topography with valleys, exhibiting highly weathered and jointed rocks with minimal soil cover. Chunchi Falls downstream represents a point of structural activity, leading to a 90-degree turn in the channel's flow path towards the confluence.

Kabini demonstrates an early propensity for floodplain formation, with the first knickpoint occurring at 69 kilometers, marked by successive elevation breaks downstream.

The Basin's peculiarities include a bedrock channel alongside cobble, pebble, gravel, and coarse sand deposition across a 50-meter channel width. The catchment region's undulating topography transitions to slightly undulating terrain downstream, with stable banks, old terraces, and well-developed flood plains near Mysore's plateau region. The channel width peaks near the confluence, reaching approximately 180 meters.

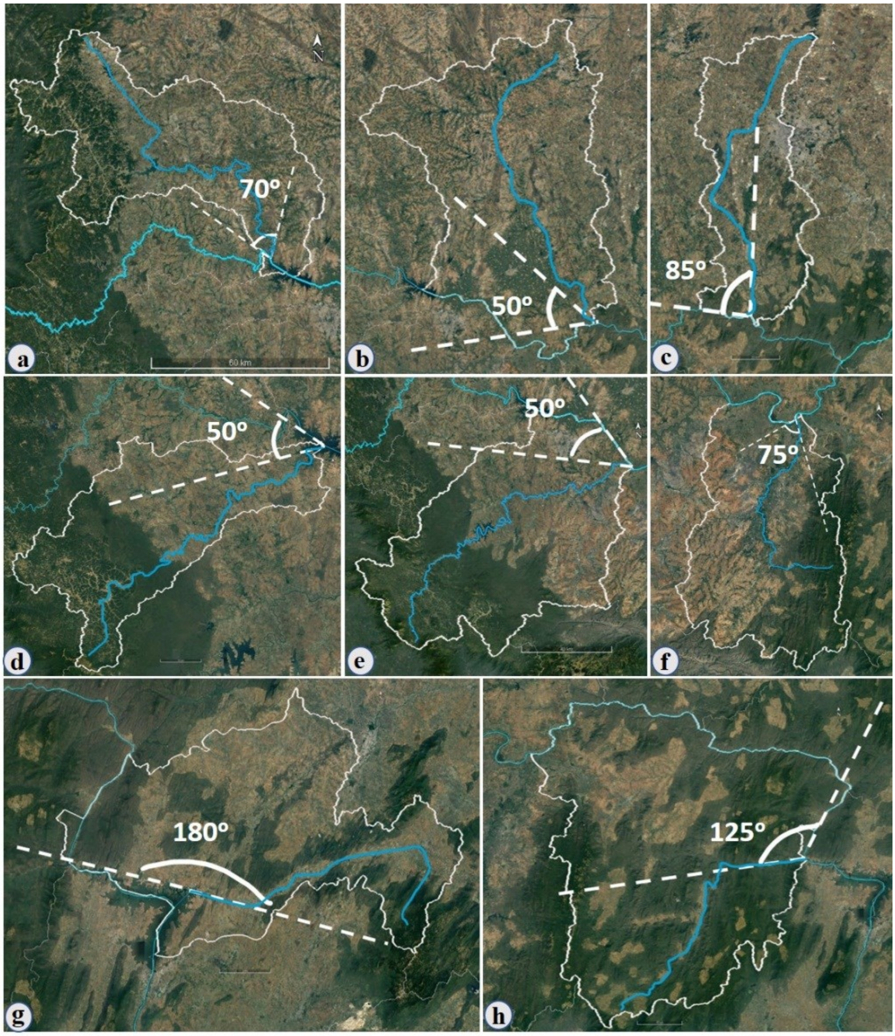

Figure 10: Confluence of (a) Hemavati shows an acute angle of 70°, the river shows straight course and successive two 90° turns in the upstream (b) Shimsha has an acute angle of 50°, (c) Arkavati has successive three near ninety degree turns in the course and an 85° confluence, (d) Lakshmantirtha shows 50° and a meandering channel course, (e) Kabini shows an acute angle of 50°, (f) Suvarnavati has an acute angle of 75°, (g) Thoppayaru has an obtuse/zero degrees angle of 180°, (h) Palar has an obtuse angle of 125° and a ninety-degree turn in the course.

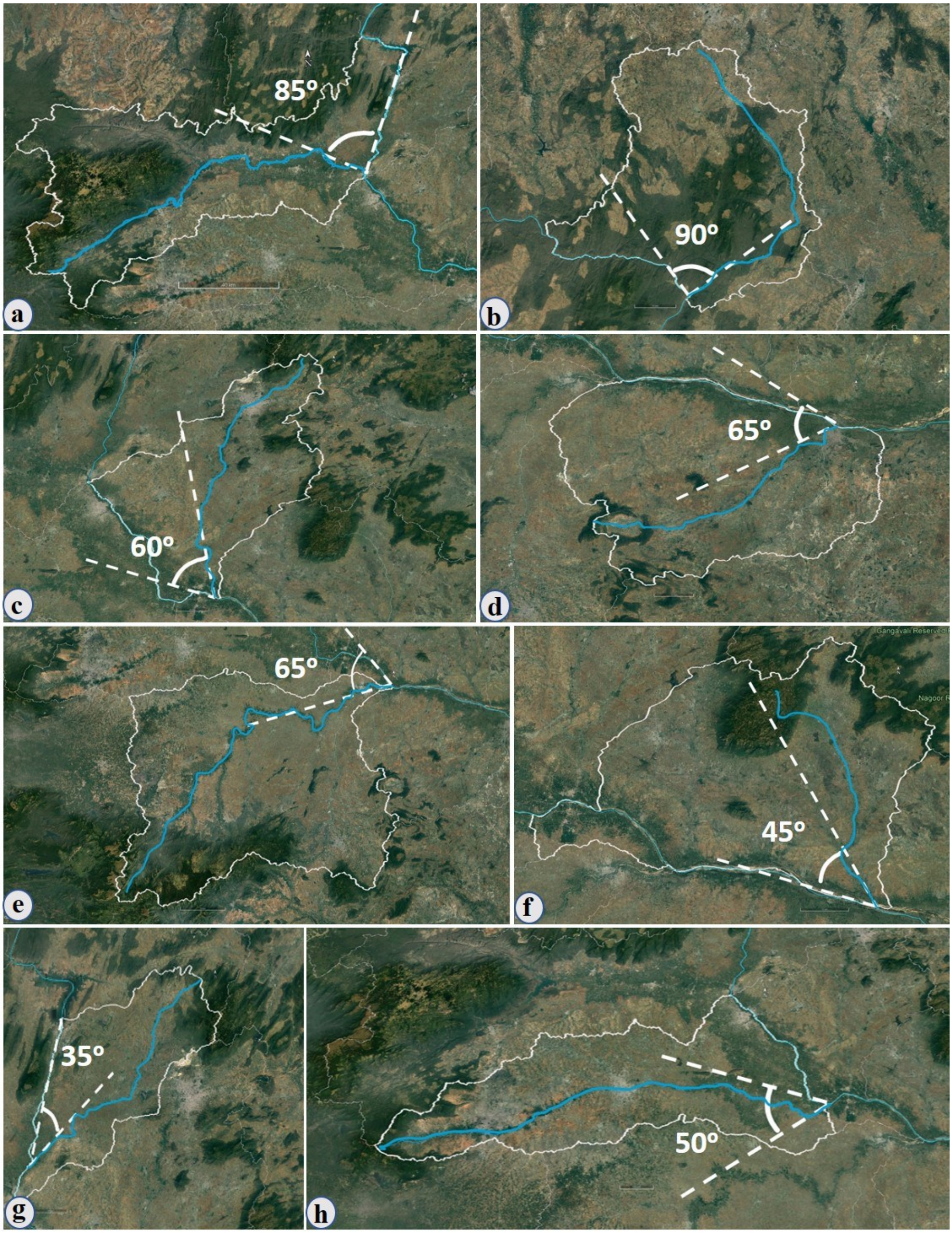

Figure 11: Confluence of (a) Bhavani is an 85° angle, (b) Chinnar has a perpendicular/90° angle and almost straight channel and a ninety-degree turn in the course, (c) Thirumanimuthar has an acute angle of 60°, (d) Kudamarutti has an acute angle of 65°, (e) Amaravati has 65° (f) Aiyaru has 45°, (g) Sarabanga has an acute angle of 35° and the channel shows obtuse angle turn in its course, (h) acute angle of 50° of Noyyal.

Lakshmantirtha's catchment is characterized by lateritic soil and dense forest cover. The undulating terrain features high elevation low relief surfaces and flood plain formation extending up to 100 meters upstream. Notably, the Basin's lone knickpoint, Iruppu Falls, is a cascade with a strike direction of N 45º E (Figure 7j). Pebble deposition characterizes the downstream course, while calcrete formations are ubiquitous. The channel, reaching base level, incises valleys and forms paleo-terraces, with a bedrock strike direction of N 150º E and a maximum channel width of 15-20 meters.

The Palar and Suvarnavati rivers, which originate in the charnockitic terrain of the Biligirirangan Hills, exhibit distinctive geomorphological characteristics. These watercourses flow through bedrock channels characterized by the presence of knickzones rather than discrete knickpoints (Figure 8e and f). This geomorphic feature suggests a complex interplay between lithology, tectonics, and fluvial processes in shaping the river profiles. In contrast, the Chinnar River displays two notable morphological features along its downstream course. Firstly, it develops extensive floodplains in its upper reaches, extending to the point where the river intersects a major fault line (Figure 3). Secondly, in its lower reaches, the river's course is marked by narrow gorges (Figure 8 n and o), persisting until its confluence point. This transition from broad floodplains to confined gorges likely reflects the river's response to structural controls and variations in bedrock erodibility.

Bhavani's catchment boasts numerous first-order streams with dendritic drainage patterns. Neo-tectonic activity is evident in boundary hills, which feature cliff faces and rocky barren surfaces. Knickpoints exhibit a consistent N 237º E strike direction in the riffle and chute structure (Figure 7f), indicating an NE-SW bedrock trend. The absence of V-shaped valleys results in the lack of terrace and floodplain formations along the channel banks. Cobble deposition persists downstream, indicating active sediment transport and selective erosion (Figure 7g).

The catchment hills surrounding Thoppaiyaru give rise to distinctive L-shaped valleys, characterized by brown-colored soil and coconut plantations. These hills are densely covered with forests and exhibit an abundance of rolled-down boulders extending up to the pediment region. Along the channel's bed and banks, numerous boulders are scattered. Upon leaving the pediment, the left bank of the channel subsides, resulting in extensive floodplain deposits, paddy fields, and natural levees. Conversely, the right bank also experiences subsidence, featuring similar floodplain deposits, paddy fields, and natural levees. Notably, a section of the channel is exposed by 3 meters en route to Anaimadaavu waterfalls, the sole cascade along the Thoppaiyaru River (Figure 8i), formed by a cascade of two successive faults of 2 meters each. Boulders from surrounding hill slopes are deposited within the narrow stream channel (5-8m), alongside sand in the channel bed. As the channel reaches its base level, it carves incised valleys and paleoterraces, with the bedrock exhibiting a strike direction of N 150º E and a maximum channel width of 15-20 meters.

The boundary hills and valleys within the Noyyal Basin display an L-shaped topography, notable for the absence of foothills and residual hillocks across the entire basin. The terrain remains relatively flat, with minimal undulations, and the channel gradient is notably low (Figure 7h). Knickpoints in the upstream section have been transformed into check dams. Upstream, the channel width measures less than 30 meters, with negligible transport of sediment load within the channel bed. Calcretized natural levees are a prominent feature of the Noyyal River, owing to the channel's operation at base level. Downstream, natural levees and flood plains extend over a wide area, maintaining consistent channel width. Near the confluence, fluvial paleo-terraces are prevalent, with incised channels reaching the bedrock. Structural controls become prominent in the vicinity of the confluence, with the channel's strike direction transitioning from N 260º W to an exact N-S orientation. Despite similarities in riverine characteristics with upstream regions, structural influences play a significant role in transforming basin characteristics to a rocky channel near the confluence of the Cauvery.

The boundary hills of Sarabanga resemble those of adjacent river basins, such as Thoppaiyaru, featuring an L-shaped topography. These hills are characterized by thin soil cover and exposed, intensely weathered rocky surfaces. Along the basin boundary, sharp peaks and cliff faces are prominent features. Upstream, the stream width is less than 10 meters, with a low water discharge rate compared to other left bank tributaries of the Cauvery. However, near the confluence, the channel widens to a maximum of 40 meters, creating vast flood plains extending up to 1 kilometer. As the channel progresses downstream, it encounters significant structural control points, including falls, cascades, and rapids (Figures 8 a&b), with a strike direction of N 45º E, aligning with the regional trending of hill ranges as observed in Google Earth Pro satellite images.

Anthropogenic interventions have altered all knickpoints along the Thirumanimuthar, resulting in the river no longer exhibiting fluvial downstream characteristics in terms of deposition and water quality. The channel's incision rate is minimal, with well-developed flood plains on either bank (Figure 8g). Despite consistent anthropogenic interventions downstream, the channel is experiencing reactivation due to tributary stream discharges and knickzone influences. Approximately 50 kilometers downstream, the right bank becomes raised, resulting in the formation of an erosional bank on the left and old terraces on the right. Cobble deposition begins at this point, coinciding with the channel's departure from the pediment region of surrounding hillocks. Aside from fault zone or knickzone interventions within the channel course, the basin exhibits minimal undulations as it progresses downstream, culminating in a sudden fall marked by structural evidence such as abrupt topographic breaks and large-scale granulite gneiss bedrock exposure. The bedrock's strike direction trends from NE-SW to E-W in the downstream course of the river.

The Amaravathi basin features a topographic arrangement of hills and foothills at its source, with the first orders originating from boundary hills as well as foothills upstream (Figure 7b). V-shaped valleys are a common feature between the hills and foothills, with thick vegetation covering the boundary hills. The terrain is characterized by undulations, structural controls, and a high density of knickpoints spanning the entire 40-kilometer river course. The most significant knickpoint is a 30-meter drop known as Thoovanam Waterfall (Figure 7a), located at Marayoor near Munnar, with bedrock orientation set at N-S. Pambar, a tributary of Amaravathi, exhibits minimal deposition up to 20 kilometers of its course. As the stream gradient decreases with the onset of pediment characteristics, cobble-boulder deposition begins on the left bank (Figure 7c). Downstream, the channel is recharged by residual hillocks with thin or no soil cover. Flat-topped hills become prominent features of the downstream course. Despite transitioning to a rocky nature due to knickzone development, the Amaravati River begins depositing sand and forming floodplains after 38

kilometers of flow. Notably, the left bank of the Amaravati River rises towards the river's downslope course.

Longitudinal profile and knickpoints

The longitudinal profile is a cross-sectional representation of the channel reach and its measurement in a linear direction downstream. It is a measure of elevation and distance covered by the stream along the geomorphic features. The profile aids in detecting knickpoints along the stream to define the transient response of the stream to variation in lithology, climate, and rock uplift and/or subsidence (Kirby et al., 2003) The link between tectonic processes and stream longitudinal profile shape has been the subject of several types of research (Ambili & Narayana, 2014). When semi-logarithmically plotted, the equilibrium stream profile on a single lithology is a straight line (Tucker & Whipple, 2002).

A more resistant lithology, an increase in shear stress, or surface uplift can all contribute to knickpoints, or the sharp reaches in the longitudinal profile (Bishop et al., 2005). A stream in equilibrium has a concave-up longitudinal profile, whereas a disruption in the gentle curve usually characterized by a “convex reach” is known as a knickpoint. Knickpoints delineate the transition between the steady state and changing landscape in each catchment. These anomalies in profiles may point to an equilibrium stream (Bishop et al., 2005) or, in some instances, a dynamic equilibrium between fluvial processes and tectonic movements, where the upstream retreat reflects changes in base-level in the upstream valley. Knickzones should respond to changes in the local lithology or the base level. Rapid river incision caused by upstream movement of knickzones creates terraces and makes valley side slopes unstable (Hayakawa and Matsukura, 2002).

The high values of R^2 for Hemavati, Shimsha, Arkavati, Kabini, Lakshmantirtha, and Palar rivers indicate that the linear model fits the data well, suggesting a strong correlation between stream slope and distance. This implies that the stream is likely in an equilibrium state, with consistent erosion and sediment transport processes along its course (Leopold et, al., 1964). Conversely, a low to very low R^2 value of Suvarnavati, Thoppaiyaru, Noyyal, Sarabanga, Thirumanimuthar, Kudamarutti, Amaravathi and Aiyaru suggests that the linear model does not fit the data well, indicating variability or non-linearity in the relationship between stream slope and distance (Figure 6). The longitudinal profiles of the Aiyaru and Kudamarutti catchments exhibit notable geomorphological characteristics, particularly in the form of a single prominent knickpoint followed by a gradual downstream course (Figure 8c and j). This distinctive profile configuration demonstrates significant variability in the fluvial system's longitudinal development. The presence of an isolated knickpoint in each of these catchments suggests a localized perturbation in the river's equilibrium profile. Such features often arise from various factors, including lithological boundaries, tectonic activity, or base-level changes. The singular nature of these knickpoints implies a discrete event or threshold in the catchment's geomorphic evolution rather than a series of ongoing disturbances. Longitudinal profiles of sixteen tributaries of the Cauvery show variable curves and gradients (Figure 6). While the Upper Cauvery Basins and the Cauvery trunk river have steep slopes along the spatial distribution of longitudinal profiles, differential uplift could be due to the high gradient of stream profiles.

In the process of discerning knickpoints within longitudinal profiles, the utilization of spatial maps, including those depicting geology, structure, and lithology, emerges as a crucial factor. These maps facilitate an understanding of the underlying terrain and its geological characteristics. The occurrence of knickpoints at lithologic boundaries can be attributed to various factors, including but not limited to differential erosion, fluctuations in base levels, and tectonic activities. These mechanisms collectively contribute to the formation and evolution of knickpoints along river longitudinal profiles, highlighting the multidimensional nature of landscape dynamics influenced by geological processes.

Knickpoints can form at lithologic boundaries due to base-level changes. A base level is the lowest point to which a river can erode its bed. When a lithologic boundary is encountered, the base level might change abruptly due to differences in rock resistance. This change can lead to the formation of a knickpoint as the river adjusts to the new base-level. (Howard, 1994) When a river encounters a lithologic boundary, such as a transition from softer to harder rock or from resistant to less resistant rock, it can also create a knickpoint where the erosion rate suddenly increases. This happens because the river's erosive power may vary depending on the type of rock it's eroding. For instance, softer rocks might erode more quickly, leading to the formation of a steeper section in the channel, while harder rocks might resist erosion, resulting in a relatively flat section. In the examination of the longitudinal profile of the trunk, a total of 24 knickpoints were identified. Notably, five of these knickpoints were found to coincide with lithologic boundaries delineating gneiss and charnockite formations. Further investigation revealed the presence of litho-boundary controlled knickpoints along prominent river systems, including the Arkavati, Hemavathi, Shimsha, and Thirumanimutharu (Figure 2). Remarkably, singular instances of knickpoints were observed at the (Suvarnavati Figure 8m) and Aiyaru (Figure 8c) rivers, suggestive of potential correlation with the underlying lithologic composition, particularly the formation of charnockite. These findings underscore the significance of lithologic boundaries in influencing the morphological characteristics of river profiles, thus warranting deeper exploration into the mechanisms governing fluvial geomorphological evolution within such contexts.

Lithologic boundaries are often associated with geological structures such as faults or folds, which can influence the course and behavior of rivers. Tectonic activity can create uplift or subsidence along these boundaries, leading to the formation of knickpoints as rivers respond to changes in topography and rock structure (Crosby et. al., 2010) These factors potentially account for the presence of knickpoints identified along the Bhavani and Sarabanga rivers. Notably, these abrupt changes in elevation are consistently observed along the Bhavani Shear Zone (BS) and Salem Arthur Shear Zone (SAS), as depicted in Figure 2. Furthermore, knickpoints dispersed throughout the Cauvery trunk stream predominantly align with shear zones or fault boundaries, as illustrated in Figures 2 and 3. These observations underscore the significance of structural features such as shear zones and faults in influencing the formation and distribution of knickpoints within fluvial networks, indicative of their role in shaping regional geomorphological landscapes.

Confluence angle and its impact on channel morphology

The upstream and downstream sections of the mainstream vary in width and depth, and these differences are related to variances in the confluence morphology. (Roy and Woldenberg 1986). In general, at a cross-section, the downstream reach is wider and deeper. It is quite challenging to perform a scientific investigation into the complexity and variations of both local and downstream features of river channel confluences because they are the crucial interfaces where two streams with different characteristics meet. River channel confluences represent a critical component of drainage system geometry, and are points at which river morphology and hydrology can change drastically (Mosley 1976). Rezaur et al. (1999) have estimated that the angle of incidence of 15°–75° has been associated with the rapid increase of the scour depth and that it occurs slowly up to 120°. Upper reaches of the basin have confluence angles between 50° and 85° which indicates an increase in the scouring capacity of the channel. The Thoppayaru River in the middle Cauvery Basin confluences at an angle of 180° to the mainstream (Figure 10g) and the Palar has a confluence angle of 125°. These two obtuse angles of confluence show anomalous characteristics within the basin while the lower tributaries have less scoring capacity since the confluence angle is less.

The obtuse angle of Thoppaiyaru and Palar suggests (Figure 12a) a relatively gentle merging of these two watercourses. Such an angle could be indicative of low sediment load or relatively equal flow rates between the tributaries, resulting in a smoother confluence. Additionally, the surrounding topography may influence the angle, with wider valleys or flatter terrain encouraging a more gradual merging of rivers. Conversely, the perpendicular angle of confluence (Figure 11b) noted at Chinnar suggests a sharper meeting point between the tributaries. This could arise from varying flow rates or sediment loads, causing one tributary to intersect the other more abruptly. It's also possible that the topography at this confluence point is characterized by steeper slopes or narrower channels, promoting a more abrupt merging of the rivers. The observation that all other tributaries exhibit acute angles of confluence implies a consistent trend in their merging patterns. Acute angles typically indicate a more forceful convergence, which could be driven by factors such as high flow rates, significant differences in water volume between the tributaries, or the presence of obstructions that force a sharper merging angle.

Furthermore, these observations could be influenced by anthropogenic factors such as human interventions like dams or diversions, which can alter natural river flow patterns and confluence angles. The confluence angles observed among the tributaries likely reflect a complex interplay of geological, hydrological, and anthropogenic factors, each contributing to the unique merging patterns observed in this study. Further analysis incorporating detailed topographic and hydrological data could provide deeper insights into the underlying processes shaping these confluence angles.

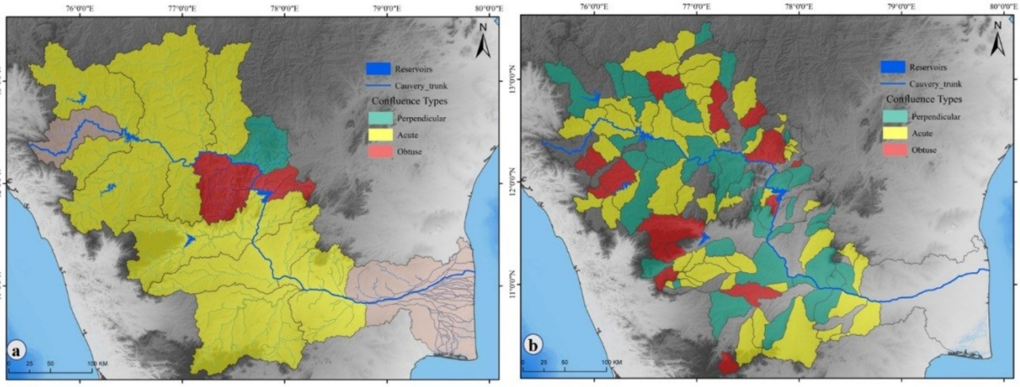

Figure 12 a: Confluence angle map for the first level tributaries, shows obtuse confluence angle in Palar and Thoppaiyaru rivers and perpendicular confluence of Chinnar River b: second level tributaries of the basin show random confluences in the Cauvery River Basin.

In examining the second-level tributaries within each subbasin, our study reveals distinct confluence angles that offer insights into the geomorphic and hydrological dynamics of the basin. It is observed that 19 smaller basins exhibit obtuse confluence angles as they join the main tributary (Figure 12b). Notably, these confluences predominantly occur in proximity to dam/reservoir installations or within flat terrain regions. This observation suggests a correlation between the obtuse angles and specific environmental conditions, notably the presence of hydraulic controls/ structures or regions characterized by gentle gradients. Such conditions likely facilitate a more gradual merging of smaller basins into the main tributary. Conversely, tributaries characterized by acute confluence angles tend to be situated in areas with steeper slopes within the basin's topography. This observation suggests a relationship between acute angles and the geomorphic features of the basin, particularly areas with pronounced elevation differentials. The sharper merging angles in these instances likely reflect the hydraulic forces generated by the rapid descent of watercourses down steep gradients. These findings underscore the influence of both topographical characteristics and anthropogenic interventions on confluence angles within the basin.

The determination of tectonic activity solely based on the confluence angle of a single tributary may lack conclusive evidence. This is because stream junction angles are susceptible to various influences beyond crustal deformation. Factors such as topographic slope at the junctions, flow discharge, sediment load within channels, sediment transport dynamics at confluences, channel bed morphology, flow velocity, turbulence, scour depth, bar size variations in channels, debris flow occurrences, groundwater seepage, instances of stream capture, channel instability, lateral migration, and channel meandering collectively contribute to the observed confluence angles. Therefore, interpreting tectonic activity based solely on a single tributary's confluence angle necessitates a thorough consideration of these multifaceted environmental dynamics Montgomery et., al 2001; Church and Zimmermann, 2007).

Conclusion

The morphometric analysis of stream profiles in the Cauvery River Basin has yielded significant insights into the complex interplay between geomorphological processes and geological factors that shape fluvial landscapes. The tributaries of the Cauvery River exhibit non-uniform concave profiles, characterized by the presence of numerous knickpoints. These discontinuities in the longitudinal profiles can be primarily attributed to structural and lithological controls, as the majority of the streams traverse diverse lithologies and intersect shear zones and faults along their courses. Notable exceptions to this pattern include the Kabini, Noyyal, and Amaravathi tributaries, which flow through relatively homogeneous lithology, and the Amaravathi, Aiyaru, Kudamarutti, and Noyyal tributaries, which do not intersect major structural features. Arkavati, Shimsha, Hemavati, Chinnar, and Bhavani, demonstrate elevated slope values, suggesting that the rate of tectonic uplift exceeds the rate of fluvial incision in these sub-basins. This observation underscores the significant influence of lithological variations and structural controls on channel gradient and overall river profile morphology. Statistical analysis of the relationship between stream slope and distance reveals varying degrees of correlation across the tributary network. High R^2 values observed for the Hemavathi, Arkavati, Kabini, Palar, and Lakshmantirtha rivers indicate a strong linear correlation between these parameters, suggesting equilibrium conditions and consistent erosional processes along their courses. Conversely, the lower and more variable R^2 values obtained for the Aiyaru, Thirumanimuthar, and Kudamarutti rivers imply non-linear relationships between stream slope and distance, highlighting the dynamic and potentially disequilibrium nature of these fluvial systems. Furthermore, the presence of obtuse and right-angle confluences, particularly evident in the cases of Thoppaiyaru, Chinnar, and Palar tributaries, provides additional evidence of structural control on the river network configuration. These angular junctions reflect the influence of underlying geological structures, such as faults or joint systems, on the drainage pattern development.

This comprehensive analysis of stream profiles in the Cauvery River Basin elucidates the complex interactions between tectonic, lithological, and fluvial processes in shaping the regional geomorphology, offering valuable insights into the evolution of this drainage system. Knickpoints at lithologic boundaries are influenced by factors like differential erosion and tectonic activities. Geological structures such as faults and folds determine river course and behavior, with tectonic activity leading to uplift or subsidence and the formation of knickpoints. Structural features like shear zones and faults shape knickpoint distribution in fluvial networks. Tributary river basins of Cauvery River Basin have unique topographic features and geomorphic processes, reflecting diverse geological settings. Longitudinal profiles indicate stream responses to geomorphic and tectonic processes, with knickpoints marking transitions between steady-state and evolving landscapes. Lithologic boundaries significantly influence knickpoint formation, with associations between structural features and abrupt elevation changes along river profiles. The complex interplay between geological processes and fluvial geomorphology is highlighted, underscoring the multidimensional nature of landscape evolution. Further research using detailed spatial mapping and modeling is needed to elucidate relationships between lithology, tectonics, and river morphology, advancing the understanding of fluvial geomorphological evolution in diverse landscapes.

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