



## OPEN Delineation of palaeochannels using DEM and spectral indices in the Gundar basin of Kadaladi region

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The identification and mapping of palaeochannels offer an essential understanding of past fluvial processes and groundwater potential, particularly in arid and semi-arid regions facing severe water stress. This study focuses on the Gundar River Basin within Kadaladi Taluk, Ramanathapuram District, Tamil Nadu, aiming to delineate palaeochannel networks using integrated geospatial techniques. Remotely sensed datasets, including Landsat 9 imagery and ASTER GDEM, were used to generate topographic derivatives such as slope, aspect, curvature, flow accumulation, and Topographic Wetness Index (TWI) along with spectral indices like NDVI, NDWI, and NDMI. False Colour Composites (FCC and SWIR-FCC) were prepared to enhance visual interpretation of buried channel patterns. A fuzzy overlay analysis, using a gamma value ( $\gamma = 0.8$ ), synthesized these inputs to classify palaeochannel suitability. Results revealed that nearly 18.3% of the basin, predominantly in the central and southeastern sectors, exhibits high palaeochannel potential. These zones are characterized by gentle slopes ( $< 3^\circ$ ), concave curvature ( $< -5$ ), high flow accumulation ( $> 2000$ ), and TWI values above 15, along with NDVI (0.35–0.50), NDWI ( $> 0.25$ ), and NDMI (0.30–0.41). These findings align with fluvial orientations from northwest to southeast, consistent with regional drainage patterns that flow towards the Bay of Bengal. Despite the absence of field validation, the results correspond well with previous studies in similar Indian basins. This research provides a robust, non-invasive framework for palaeochannel detection, supporting future groundwater recharge planning and paleohydrological reconstructions in coastal, water-stressed environments, such as Kadaladi Taluk.

**Keywords** Palaeochannel, Remote sensing, GIS, Fuzzy overlay, Groundwater recharge, Fluvial geomorphology, Gundar river basin

Groundwater constitutes a crucial freshwater resource supporting domestic, agricultural, and industrial demands globally, particularly in regions experiencing irregular surface water availability<sup>1</sup>. Around one third of the world's population relies on groundwater for irrigation and drinking, particularly in coastal, semi-arid, and arid regions where surface water supplies are intermittent or non-existent<sup>2</sup>. Since groundwater in India provides 85% of residential needs and more than 60% of agriculture, its management and preservation are essential for the socioeconomic growth<sup>3</sup>. Tamil Nadu, located in the southern part of India, is one of the most water-stressed states due to uneven rainfall distribution, over extraction, rapid urbanization, and a complex hydrogeological framework<sup>4</sup>. This scarcity is more pronounced in coastal and arid regions, such as the Ramanathapuram district, where Kadaladi Taluk is located.

Palaeochannel is a buried remnant of ancient river systems which have gained increasing hydrogeological importance due to their role in enhancing groundwater recharge and potentially improving water quality<sup>5</sup>. Typically composed of sand, gravel and other permeable materials, palaeochannels exhibit higher porosity and

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transmissivity, allowing for rapid infiltration and lateral movement of groundwater<sup>6</sup>. These subsurface channels often act as natural recharge pathways and storage zones, especially in arid or coastal settings with limited aquifer recharge<sup>7</sup>. In arid and semi-arid regions, palaeochannels often contain coarse-grained, permeable sediments that offer favourable conditions for groundwater recharge and storage. Palaeochannels may contain fresher and cleaner groundwater than neighbouring formations due to their filtration, dilution, and reduced vulnerability to surface contamination. Therefore, identifying palaeochannels using remote sensing and GIS has become a valuable approach in groundwater resource planning and quality assessment<sup>8,9</sup>.

Although palaeochannels have the potential to provide high-quality water, their effectiveness is influenced by sediment composition, depth, recharge potential, and local geochemistry<sup>10</sup>. In coastal zones, over extraction may cause palaeochannels to act as a pathway for saline intrusion rather than recharge<sup>11</sup>. Moreover, the presence of geogenic contaminants like fluoride, uranium, or arsenic in buried sediments can compromise water quality in these zones<sup>12</sup>. Thus, a comprehensive understanding that combines palaeochannel mapping with hydrochemical analysis is essential<sup>13</sup>.

The integration of remote sensing and geographic information systems (GIS) technologies has significantly advanced the detection and mapping of palaeochannels<sup>14</sup>. Digital elevation models, satellite imagery, and geophysical surveys have all improved the feasibility of palaeochannel identification<sup>15,16</sup>. Recent multispectral studies<sup>17</sup>, demonstrate how indices like NDVI, NDWI, and SWIR-based composites are particularly effective in detecting moisture-rich or clay-rich subsurface features, characteristics commonly associated with palaeochannel sediments. These tools facilitate the visualisation of subtle terrain variation, vegetation anomalies, soil moisture patterns, and spectral signatures that may be indicative of buried channels, but site-specific confirmation is still needed<sup>18</sup>. An integrated framework for sustainable groundwater exploration, particularly in water-stressed areas, is provided by connecting palaeochannel zones with groundwater quality data<sup>19</sup>.

In recent years, the integration of remote sensing and GIS for delineating palaeochannels and assessing groundwater has gained significant momentum across India. Nationwide studies have demonstrated the value of combining multi-source satellite imagery, terrain derivatives, and geophysical data to successfully identify subsurface palaeochannels and groundwater potential zones. For instance, Bhadra et al.<sup>7</sup> effectively merged Landsat, Sentinel-1 SAR, and high-resolution resistivity surveys in the Punjab Sutlej basin, revealing palaeochannels with coarse sand deposits over 40 m thick, which function as high-yield aquifers. Morphometric analysis is highly effective in interpreting drainage evolution, basin response, and subsurface geomorphic controls, all of which are directly relevant for identifying palaeochannel pathways in low-relief terrains<sup>20</sup>.

Sathiyamoorthy et al.<sup>21</sup> employed an integrated remote sensing, GIS and AHP-based methodology to delineate groundwater potential zones in the coastal areas of Cuddalore District, Tamil Nadu, effectively synthesising thematic layers such as land use/land cover, soil, slope, geology, and drainage to enhance groundwater resources sustainability in complex coastal hydrogeological settings. Gnanachandrasamy et al.<sup>22</sup> delineated groundwater potential zones in Ariyalur district using weighted overlay techniques based on drainage, lineaments, and soil layers. Analysed hard rock aquifers in Perambalur district through remote sensing and GIS, correlating satellite-derived fracture maps with field fracture data to locate zones suitable for artificial recharge structures.

Modak & Das<sup>23</sup> carried out an integrated study in the coastal Vattamalaikarai basin of Tamil Nadu that combined in-depth field investigation with thematic layer analysis, such as geomorphology, drainage patterns, soil characteristics, and land use, to determine appropriate sites for groundwater recharge structures. To increase the effectiveness of artificial recharge initiatives in the basin, their strategy placed a strong emphasis on customising interventions to site-specific lithological and hydrological conditions. Karunanidhi et al.<sup>24</sup> A similar synergistic approach was used in the Kadavananar sub-basin, combining satellite-derived watershed parameters with vertical electrical sounding (VES) data. This enabled them to accurately determine hydrogeological conditions and subsurface lithological variations, which are crucial for selecting promising areas for constructing recharge infrastructure.

In other coastal regions of Tamil Nadu, such as Sivagangai and Cuddalore districts, similar methodological frameworks have been adopted<sup>25</sup>. Vellaikannu et al.<sup>26</sup> utilized a GIS-based Analytic Hierarchy Process (AHP) model in Sivagangai to systematically prioritise groundwater recharge zones by incorporating multiple thematic layers, including slope, soil, land use/land cover, geology, and lineament density. This multi-criterion decision-making approach allowed for objective zoning of recharge potential areas, particularly in regions vulnerable to seasonal water stress. Likewise, Sathiyamoorthy et al.<sup>21</sup> applied a GIS-AHP framework in the Cuddalore coastal belt to identify and map suitable recharge sites, considering both natural terrain features and anthropogenic influences. Collectively, these studies underscore the applicability and strength of GIS AHP models and integrated geospatial methods in delineating recharge hotspots in coastal hydrogeological environments, where groundwater management in both critical and complex.

Groundwater scarcity and deteriorating water quality have emerged as critical challenges in Kadaladi Taluk, which is due to the excessive extraction and minimal natural recharge and seawater intrusion. The overdependence on groundwater for agricultural and domestic use, combined with inadequate scientific exploration of aquifer systems, has led to declining water tables and increased salinity levels. These issues are severe in rural and coastal areas, where access to safe and reliable water resources is limited. Identifying naturally occurring areas favourable to groundwater occurrence, such as palaeochannels, is a possible alternative to treatments like desalination and artificial recharge, which can be expensive or challenging. Despite the increasing application of geospatial technologies in hydrogeological investigations across India, systematic Palaeochannel mapping in Kadaladi Taluk is lacking. While several studies have examined groundwater conditions in Ramanathapuram district, these have largely focused on hydrochemical assessment or borehole data, without integrating geomorphic or palaeodrainage perspectives. This gap in Kadaladi not only restricts our understanding of subsurface hydrological channels but also limits the potential to optimize groundwater resource management based on historical fluvial imprints.

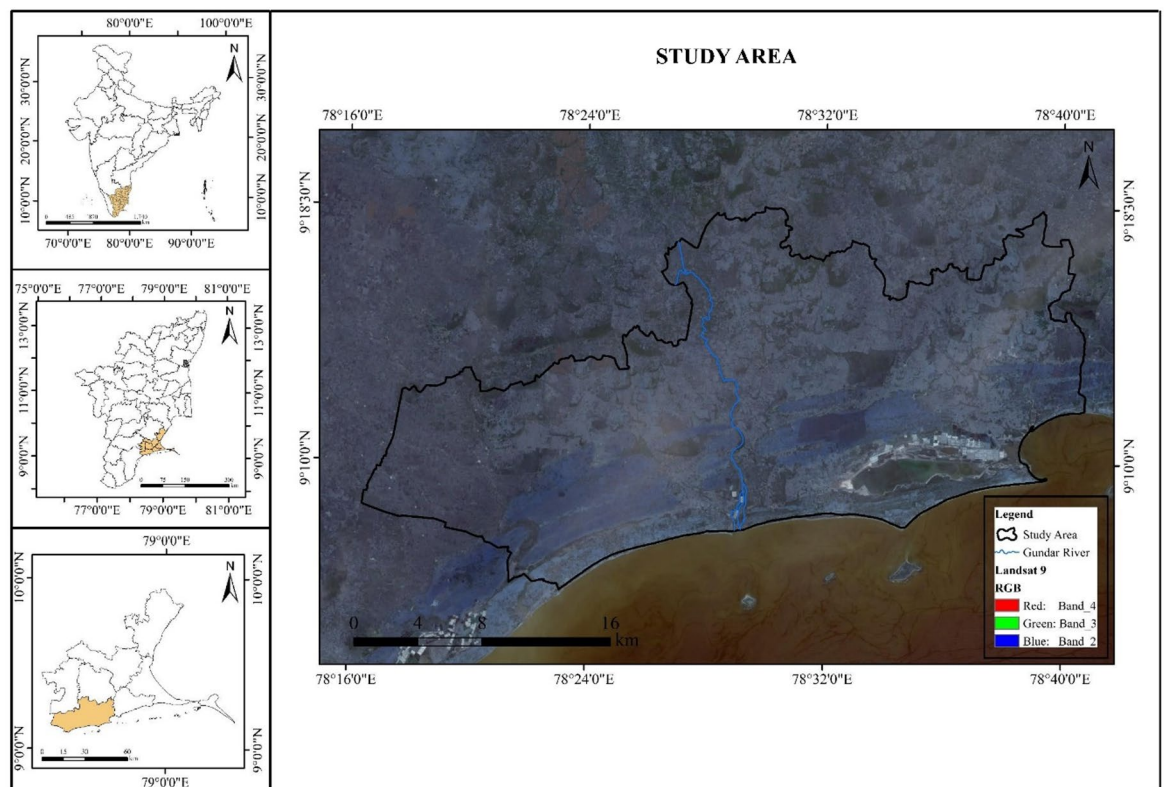
The present study is undertaken to bridge this knowledge gap by applying an integrated remote sensing and GIS-based approach to investigate palaeochannels in Kadaladi Taluk. The Study specifically aims to delineate palaeochannel networks using multi-source satellite imagery and terrain analysis derivatives, interpret the spatial and geomorphic features of the palaeochannels that have been identified, and evaluate their hydrogeological significance, especially about the potential for groundwater recharge and the spatial distribution of water quality.

This study is based on the theory that, due to their lithological composition and permeability, palaeochannels in Kadaladi Taluk serve as preferred areas for storing groundwater and may also contain aquifers of comparatively higher quality. It is confirmed that this would provide a scientifically strong method for prioritising zones for groundwater extraction and artificial recharge. In terms of the environment, the study identifies potential recharge locations that can be maintained or improved, thereby increasing the sustainability of aquifers. Delineating palaeochannel zones can improve water access for agriculture and domestic usage and assist local farmers and communities in reducing their dependency on saline or deteriorating water sources. In terms of management, it provides decision-makers with economic, spatially explicit tools for organizing and overseeing groundwater interventions in an environment with limited sources. The study focuses on identifying and interpreting palaeochannels in Kadaladi Taluk using remote sensing and GIS. To locate and analyse fluvial signatures, it uses spectral composites (FCC, and SWIR-FCC), terrain parameters (elevation, slope, aspect, flow direction and accumulation), and satellite-derived inputs including NDVI, NDWI, and NDMI.

### Study area

The Study Area, Kadaladi Taluk, is shown in Fig. 1 and is situated in the western part of Ramanathapuram District, Tamil Nadu, forming an important part of the east-flowing Gundar River Basin. The Taluk covers approximately 612 square kilometres and lies between 29 m above mean sea level, showing a gentle west-to-east gradient. This low-lying gradient, common in coastal plains, creates depositional conditions that are ideal for the formation of palaeochannels. The research region is bordered by crystalline foundation rocks inland and sedimentary topography toward the coast, with the river eventually draining into the Bay of Bengal. The region is characterized by a semi-arid tropical climate, with an average annual rainfall of approximately 800 mm, predominantly received during the northeast monsoon (October–December) and with lesser contributions from the southwest monsoon (June–September). The mean annual temperature ranges from 25 °C to 37 °C, with high evapotranspiration and seasonal water scarcity. The Gundar River is mostly ephemeral, flowing only during monsoonal periods, while the dry riverbeds and abandoned meander belts hint at past fluvial activity.

Geologically, Kadaladi is underlain by Quaternary alluvium, sandstone, and weathered gneissic formations. These features, combined with its geomorphic setting, have led to the formation of palaeochannel networks,



**Fig. 1.** Location Map of the Kadaladi region. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

particularly concentrated in the central and southeastern sectors. The buried or relic channels are not easily traceable on the surface due to alluvial burial and anthropogenic modifications, but are detectable through remote sensing analysis. Thus, the study area provides an excellent setting for investigating palaeochannels using geospatial tools. Mapping these features facilitates an understanding of the historical fluvial regime and supports groundwater exploration, aquifer recharge planning, and regional land-use management in this water-stressed coastal tract of southern Tamil Nadu.

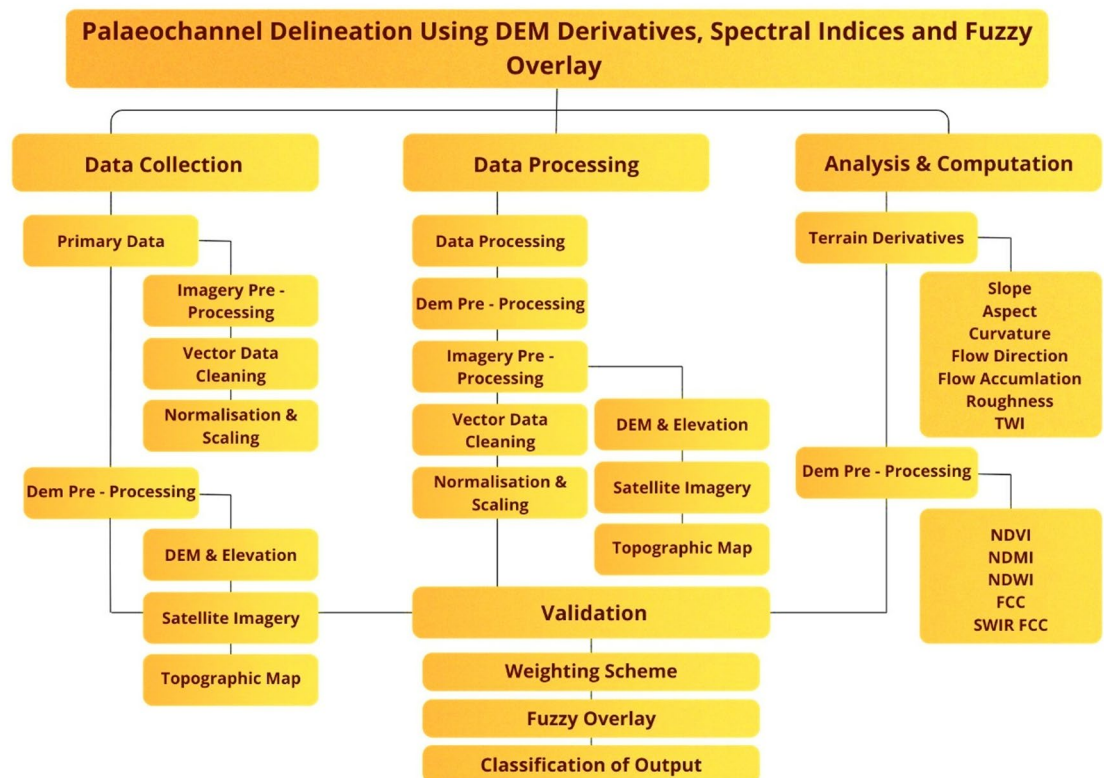
## Methodology

The methodology adopted for delineating palaeochannel networks in the Gundar River Basin, particularly within Kadaladi Taluk of Ramanathapuram District, is based on a comprehensive geospatial framework that integrates remote sensing data, digital terrain analysis, multispectral interpretation, and fuzzy logic-based spatial modeling. The methodological workflow was designed in a progressive manner, beginning with data acquisition and pre-processing, followed by the derivation of terrain and spectral indices, and concluding with their integration through fuzzy overlay analysis to identify potential palaeochannel zones. All spatial analyses and image processing were carried out using ArcGIS 10.8 and ERDAS Imagine software environments. Figure 2 illustrates the overall methodological framework adopted in this study.

## Data and materials

The study utilised multi-source remotely sensed datasets, digital elevation data, and geospatial ancillary layers selected for their relevance to palaeochannel detection in low-relief coastal environments. Multispectral satellite imagery was obtained from the Landsat-9 Operational Land Imager (OLI) sensor, sourced from the USGS Earth Explorer platform. Cloud-free scenes from the post-monsoon period of 2022–2023 were selected to minimise seasonal bias and enhance detection of surface moisture and vegetation responses associated with buried fluvial features. Two Landsat-9 OLI scenes (Path 143/Row 53), acquired on 14 December 2022 and 17 January 2023, each with less than 2% cloud cover, collectively covered the entire 612 km<sup>2</sup> extent of the Gundar River Basin. The multispectral bands in the visible, near-infrared (NIR), and shortwave infrared (SWIR) regions provided the basis for spectral index computation and colour composite generation.

Topographic information was derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) Version 3, which provides elevation data at a spatial resolution of 30 m across the entire study area. This dataset served as the primary input for terrain-based analysis, enabling the extraction of elevation, slope, aspect, curvature, flow direction, flow accumulation, and the Topographic Wetness Index (TWI), all of which are critical for identifying subtle geomorphological and hydrological signatures of palaeochannels. Administrative boundary data and base maps required for spatial referencing and cartographic representation were obtained from the Survey of India and relevant governmental



**Fig. 2.** Flowchart depicting the geospatial approach for palaeochannel delineation.

sources. To ensure spatial consistency across datasets, all layers were re-projected to the Universal Transverse Mercator (UTM) coordinate system, Zone 44 N, using the World Geodetic System 1984 (WGS-84) datum.

### Terrain derivatives

Terrain derivatives, including slope, aspect, curvature, flow direction, flow accumulation, and the Topographic Wetness Index (TWI), were computed from the DEM using the Spatial Analyst tools in ArcGIS. The slope of the terrain was computed using the standard mathematical expression shown in Eq. (1), and the remaining terrain parameters were generated through hydrological and surface analysis modules to capture variations in topography and drainage behaviour. Collectively, these parameters represent the terrain morphology and hydrological response of the basin and served as essential indicators for identifying subtle palaeochannel depressions that may not be evident in raw imagery or elevation data alone.

$$Slope = \tan^{-1} \left( \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \right) \quad (1)$$

Where,  $\left(\frac{\partial z}{\partial x}\right)$  and  $\left(\frac{\partial z}{\partial y}\right)$  represent the change in elevation in the x and y directions, this method follows the algorithm outlined by Horn, (1981)<sup>27</sup> for computing slope from gridded elevation data. The aspect of the slope, indicating the directional orientation of terrain faces, was computed from the DEM to assess alignment with prevailing drainage trends (Burrough & McDonnell, 1988)<sup>28</sup>. Curvature, a second-order derivative of elevation, was computed to identify geomorphological depressions and ridges. It was calculated using the Eqs. 2,

$$Curvature = \frac{d^2 z}{dx^2} + \frac{d^2 z}{dy^2} \quad (2)$$

This approach to curvature estimation is based on the method described by Zevenbergen & Thorne, (1987)<sup>29</sup>. Flow direction and flow accumulation were derived using the D8 algorithm. Flow direction raster assigned a direction to each pixel based on the steepest descent to an adjacent cell<sup>30</sup>. Flow accumulation, which calculates the number of upstream cells contributing to flow, identified convergent flow lines and linear depression<sup>31</sup>. To analyse soil moisture distribution, the Topographic Wetness Index (TWI) was calculated using Eqs. 3,

$$TWI = \ln \left( \frac{a}{\tan \beta} \right) \quad (3)$$

Where  $a$  is the upslope contributing area per unit contour width, and  $\beta$  is the local slope in radians.

### Multispectral imagery

#### Computation of spectral indices

Spectral interpretation was conducted using Landsat 9 data<sup>14</sup>. The Normalized Difference Vegetation Index (NDVI) was calculated using Band 5 (NIR) and Band 4 (Red) to assess vegetation strength as per the Eqs. 4,

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (4)$$

Normalized Difference Water Index (NDWI), is an indicative of surface moisture and shallow water presence, was computed using Band 3 (Green) and Band 5 (NIR) which is calculated using the Eq. (5),

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \quad (5)$$

The Normalized Difference Moisture Index (NDMI) was used to detect soil and vegetation moisture content, employing Band 5 (NIR) and Band 6 (SWIR) using the Eq. (6),

$$NDMI = \frac{(NIR - SWIR)}{(NIR + SWIR)} \quad (6)$$

These indices have been widely applied in remote sensing studies for groundwater potential mapping, vegetation health assessment, and moisture analysis<sup>32,33</sup>. The computation of NDVI, NDWI, and NDMI characterizes vegetation strength, water presence, and soil/vegetation moisture dynamics. False Colour Composites (FCC) and SWIR-based composites were generated to enhance the visual interpretation of linear to curvilinear tonal anomalies. These enhanced composites helped distinguish subtle palaeochannel fills that might otherwise remain obscured in natural-color imagery.

#### Band composition and colour composites

False Colour Composites (FCCs) were generated using Band combinations 8, 4, and 3 (NIR, Red, Green) to visualize surface features. In these composites, vegetated areas appear red, while linear and curvilinear features indicative of relict channels are visible in sinuous formations across the basin<sup>34</sup>. Additionally, SWIR-FCCs were

generated using Bands 12, 11, and 8, which helped identify clay-rich soils and variations in moisture content, supporting further identification of palaeochannel tracts. To integrate the diverse datasets and systematically delineate paleochannel zones, a Fuzzy Overlay Analysis was conducted using the fuzzy logic toolset in ArcGIS. Each thematic layer's slope, curvature, flow accumulation, TWI, NDVI, NDWI, and NDMI were standardized using fuzzy membership functions, assigning values between 0 (least suitable) and 1 (most suitable). High membership was assigned to slope < 3°, curvature < -5, TWI > 15, NDWI > 0.25, and NDMI > 0.30.

### Fuzzy overlay analysis

A fuzzy gamma overlay with  $\gamma = 0.8$  was used to combine the layers, balancing the effects of fuzzy sum and fuzzy product and it is employed using the Eq. (7),

$$\text{Fuzzy Overlay Result} = \left( \prod_{i=1}^n x_i \right)^{1-\gamma} \times \left( 1 - \prod_{i=1}^n (1 - x_i) \right)^{\gamma} \quad (7)$$

Where  $x_i$  is  $i^{\text{th}}$  thematic layer's fuzzy membership value<sup>35</sup>. To overlay, each thematic raster was converted into fuzzy membership values ranging from 0 to 1 based on its relative suitability for palaeochannel occurrence. The membership assignment followed empirically derived thresholds such as slope < 3°, curvature < -5, TWI > 15, NDWI > 0.25, and NDMI > 0.30, ensuring that each parameter contributed proportionally to palaeochannel identification. A fuzzy gamma overlay ( $\gamma = 0.8$ ) was then applied to integrate all thematic layers, providing an optimal balance between the additive (fuzzy sum) and restrictive (fuzzy product) influences among the factors. The high degree of correlation between topographic, spectral, and fuzzy outputs lends credibility to the interpreted palaeochannel networks, considering that actual validation techniques, such as resistivity surveys, sediment coring, or ground-penetrating radar (GPR), were not employed in this study due to resource limitations. The technique provides a spatially accurate, repeatable, and non-invasive way for mapping palaeochannels in coastal and semi-arid alluvial environments like the Gundar Basin.

### Results and discussion

The present study delineated the palaeochannel networks of the Gundar River Basin using integrated satellite remote sensing and GIS techniques. The results are based on the analysis of ASTER GDEM-derived topographic derivatives, including DEM, slope, aspect, curvature, flow direction, flow accumulation, and TWI, as well as Sentinel-2 multispectral indices (NDVI, NDWI, NDMI), and False Colour Composites (FCC and SWIR-FCC). A fuzzy overlay analysis was employed to integrate these layers and delineate palaeochannel zones.

#### DEM and terrain derivatives

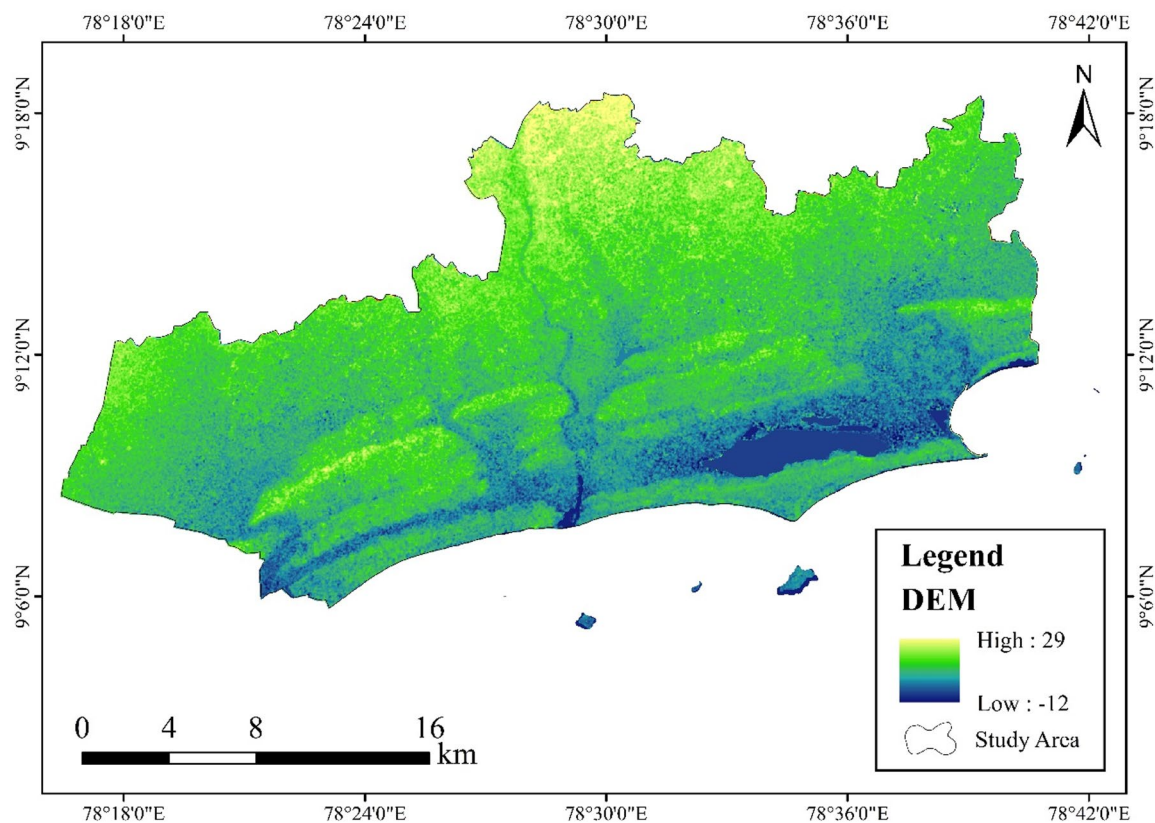
The Digital Elevation Model shown in Fig. 3 of the Gundar Basin reveals a general west-to-east gradient, with elevations ranging from 29 m in the uplands of the northwest to -12 m in the eastern coastal zones. This elevation pattern reflects a gentle west-east gradient typical of low-relief coastal plains, and such subdued relief plays a significant role in the development and preservation of palaeochannels.

The slope map depicted in Fig. 4, derived from the DEM, shows predominantly low gradients (< 5°) across the basin, with steeper slopes confined to isolated upland mounds and structural highs. The slope analysis classified the terrain into different slope categories, with 82.6% of the total area exhibiting slopes below 3°, in which the most dominant class of 63.2% comprises slopes between 0.5° and 2.5°. The predominance of slopes below 3° strongly favours fluvial deposition and enhances the preservation potential of palaeochannel systems in the basin.

These low-slope regions are typical depositional environments favourable for sediment accumulation and fluvial migration. The aspect map shown in Fig. 5 reveals that the terrain is mainly oriented toward the east (13.2%), southeast (11.4%), and south (15.6%). The presence of east- and southeast-facing slopes supports the hypothesis of paleo-drainage directed toward the Bay of Bengal. These slope orientations also align well with the detected dendritic drainage traces, strengthening the interpretation of buried and reworked fluvial channels, further confirming the suitability of this region for the development of low-energy meandering river systems and associated palaeochannels.

The flow direction shown in Fig. 6 and the flow accumulation in Fig. 7, generated using the D8 flow model, revealed coherent runoff patterns that point eastward and southeastward, demonstrating well-defined drainage patterns in the central and western sectors of the basin. These converge into broad, dendritic patterns in the east, suggesting historical reorganization of the old stream courses. The flow accumulation raster, however, presents anomalously high values across expansive tracts of the basin, while the existing channels exhibit relatively lower accumulation. This behaviour arises from the extremely low-relief topography of the Gundar Basin, wherein the D8 algorithm distributes large upslope contributing areas into subtle surface depressions, resulting in artificially inflated accumulation values. Conversely, present river channels that have undergone sink-filling during DEM conditioning receive fewer contributing cells and therefore show reduced flow accumulation. Such discrepancies are well-documented in alluvial lowlands and represent artifacts of DEM-driven drainage modeling rather than true hydrological conditions. Curvature analysis of Fig. 8 highlights the geomorphometric nature of the landscape, which revealed a wide range from -18.7 to +21.4. Positive curvature values of > 10 denote convex features (ridges) observed in elevated mounds and structural ridges. Negative curvature values of < -5 reflect concave depressions (valleys), which correlate with sediment accumulation zones and palaeochannel signatures. Values around zero indicate planar surfaces. The concave features, primarily observed in the central and south-eastern parts, match well with inferred palaeochannel corridors.

The Topographic Wetness Index (TWI), as shown in Fig. 9, effectively identifies moisture-retaining zones across the terrain. TWI values in the basin range from 3.1 to 19.6, with higher values concentrated in the central



**Fig. 3.** Digital elevation model derived from ASTER GDEM. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

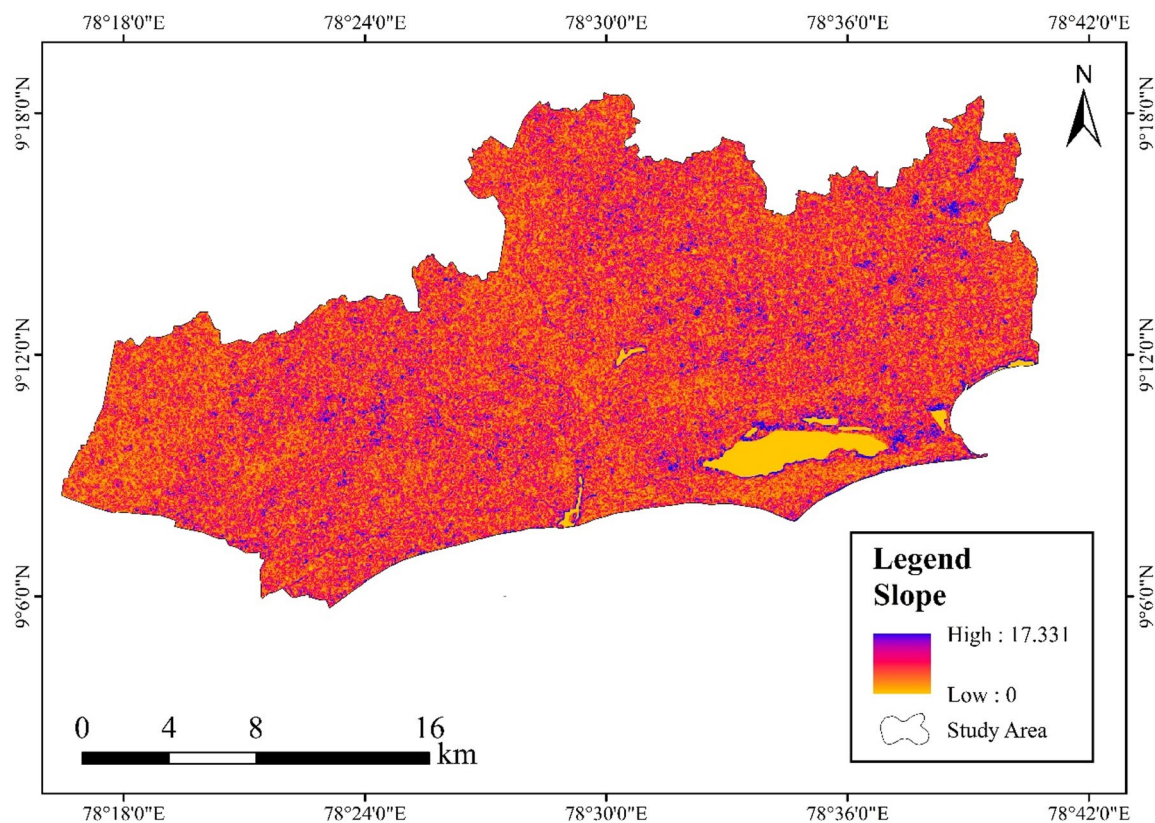
and eastern portions. TWI values exceeding 15 cluster prominently along broad depressions, particularly in the central and southeastern sectors, lending further support to palaeochannel hypotheses. These high-TWI zones correspond to areas of historical water accumulation and prolonged soil moisture retention, frequently overlapping with flow accumulation and curvature outputs, thereby reinforcing their interpretation as potential palaeochannel tracts.

### Spectral indices and multispectral analysis

Vegetation and moisture indices derived from Landsat 9 imagery were used to further confirm geomorphological interpretations. The Normalized Difference Vegetation Index (NDVI) depicted in Fig. 10 showed values ranging from  $-0.06$  (indicative of bare or built-up land) to  $0.65$  (dense vegetation). High NDVI values, ranging from  $0.35$  to  $0.50$ , were spatially distributed along curvilinear patches that ran northwest to southeast in the central and eastern portions of the study area. These zones, characterised by high TWI and gentle slopes, align with older river channels that have evolved into fertile agricultural lands, enriched by sediment deposition and enhanced moisture-retaining soil textures that support present-day vegetation. The occurrence of NDVI values between  $0.35$  and  $0.50$  along sinuous vegetated alignments is particularly significant, as such patterns are consistent with moisture-enriched palaeochannel sediments.

The Normalized Difference Water Index (NDWI), depicted in Fig. 11, shows values ranging from  $0.01$  to  $0.37$ . Moisture-enriched tracts with  $NDWI > 0.25$  were predominantly observed in the southeastern and central eastern region of the study area. These zones correspond with surface depressions, and high TWI values likely correspond to moist soils and shallow groundwater tables, indicating high water retention capacity typically associated with fine-grained sediment fills within palaeochannel environments. The NDWI thresholds ( $> 0.25$ ) clearly delineate areas of enhanced moisture retention that align with other topographic indicators of palaeochannel depressions.

The Normalized Difference Moisture Index (NDMI), as shown in Fig. 12, ranged from  $0.16$  to  $0.41$ , capturing variations in vegetation and soil moisture through the SWIR and NIR bands. Moderate to high NDMI values, ranging from  $0.30$  to  $0.41$ , were primarily observed along northwest-to-southeast trending linear zones in the central and northeastern parts of the basin. These patterns suggest consistent moisture availability, likely driven by subsurface water flow and enhanced capillary action in fine-textured sediments with typical characteristics of palaeochannel environments. The elevated NDMI values correspond with zones of active agriculture and residual moisture concentrations, particularly along former meandering paths, providing further evidence



**Fig. 4.** Slope in degrees. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

of differential moisture retention associated with buried palaeochannel soils. The NDMI range of 0.30–0.41, coinciding with linear, moisture-rich belts, further strengthens the interpretation of relict channels.

The False Colour Composite (FCC) shown in Fig. 13, generated using Landsat 9 Bands 5 (NIR), 4 (Red), and 3 (Green), clearly differentiates between vegetated areas in red tones and reveals multiple sinuous, linear, and curvilinear features extending across the central belt of the basin in a northwest-southeast orientation.

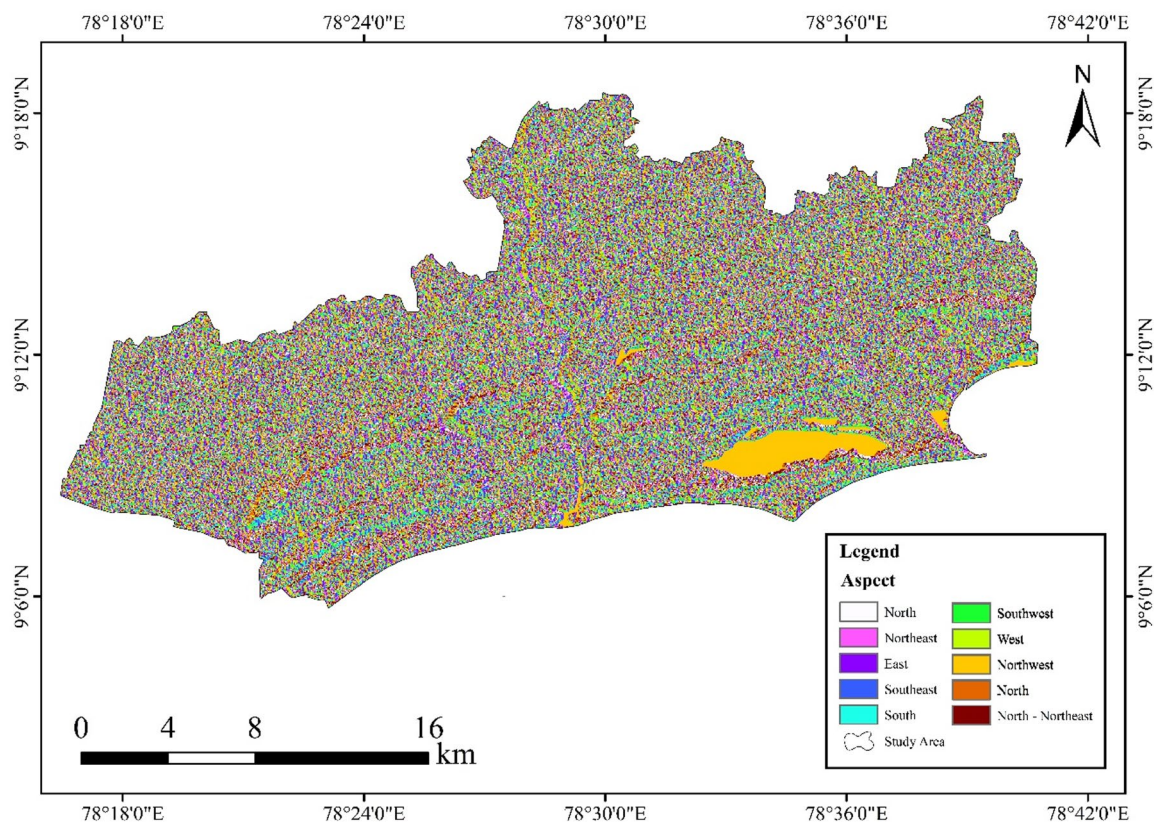
These red-toned corridors correspond to elongated, moisture-retentive zones likely supported by subsurface moisture along relict channel pathways. The SWIR-FCC shown in Fig. 14, generated using Bands 12, 11, and 8, further emphasizes soil and moisture variations, delineating bright contrasts and subtle tonal shifts, particularly in the southern and northeastern sectors. These tonal variations indicate clay-rich palaeochannel fills whose geometry corresponds closely to palaeodrainage orientations. Both FCC and SWIR composites consistently reveal elongated tonal anomalies that are highly suggestive of historical channel migration and sediment infill.

Palaeochannel candidates in this study were delineated only where at least three diagnostic conditions spatially overlapped: concave curvature ( $< -5$ ),  $TWI > 15$ ,  $NDWI > 0.25$ ,  $NDMI > 0.30$ ,  $NDVI$  between 0.35 and 0.50, and sinuous tonal anomalies evident on FCC and SWIR composites. This multi-criteria approach ensured high interpretive confidence, linking spectral moisture responses, topographic depressions, and geomorphological signatures to identify robust palaeochannel traces.

### Fuzzy overlay and palaeochannel mapping

The fuzzy overlay analysis served as a robust integrative framework for delineating potential palaeochannel zones by synthesizing multiple terrain and spectral-derived thematic layers. A fuzzy gamma operator with  $\gamma = 0.8$  was employed to balance the restrictive influence of the fuzzy product and the permissive influence of the fuzzy sum, thereby enhancing the reliability of the composite output while avoiding extreme bias toward any single parameter. All input rasters, including slope, curvature, flow accumulation, Topographic Wetness Index (TWI), NDVI, NDWI, and NDMI, were standardized to fuzzy membership values ranging from 0 to 1, where values approaching 1 represent conditions most favourable for palaeochannel occurrence.

The fuzzy overlay output shown in Fig. 15 identifies approximately 18.3% of the basin as exhibiting high palaeochannel potential. These zones are predominantly concentrated within the central and southeastern portions of the Gundar Basin and coincide with areas characterized by slopes below  $3^\circ$ , elevated TWI values, and moisture-enriched spectral responses ( $NDWI > 0.25$  and  $NDMI > 0.30$ ). These spatial clusters correspond to sinuous depressions, characterized by concave curvature values below  $-5$ , and NW–SE trending geomorphometric alignments that reflect the relic signatures of former fluvial pathways.



**Fig. 5.** Aspect map showing the directional orientation. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

The overlap of spectral moisture indicators (NDVI 0.35–0.50, NDWI > 0.25, NDMI 0.30–0.41) with topographic depressions and high-flow accumulation zones reinforces the palaeochannel hypothesis, suggesting the presence of fine-textured, water-retentive sediment fills typical of abandoned river tracts. Concave curvature values (< -5) observed in these regions further support their interpretation as erosional-depositional features shaped by historical fluvial processes.

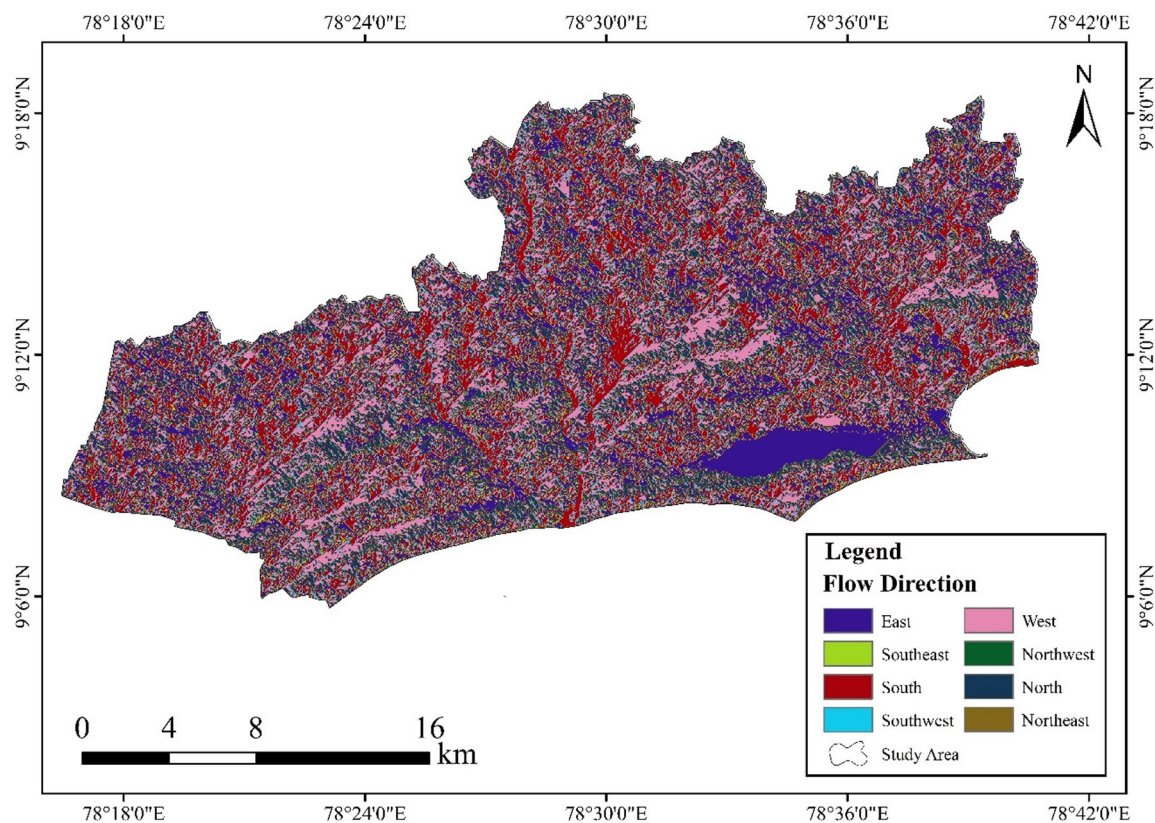
Through the fuzzy logic approach, the study effectively integrates diverse geospatial parameters into a unified probabilistic model, enabling greater spatial coherence and interpretive confidence than would be possible with individual thematic layers alone. The resulting palaeochannel map highlights sinuous, curvilinear depressions embedded within the broader alluvial plain, consistent with migratory pathways of historical drainage systems. This multi-criteria integration provides a spatially accurate and geologically justified representation of buried or faintly preserved palaeochannel networks across the basin.

### Spatial configuration and palaeo geomorphological significance

The spatial configuration of the identified palaeochannels within the Gundar River Basin reveals a compelling set of geomorphological patterns. The channels exhibit distinct meandering forms, which are characteristic of dynamic lateral migration processes that occurred in the geological past. These sinuous patterns are consistent with the sedimentary behavior of low-gradient river systems operating under relatively stable, low-energy conditions. The general orientation of the palaeochannels follows a northwest-to-southeast directional trend, which aligns with the natural slope of the terrain and the regional drainage flow toward the Bay of Bengal. In several instances, the palaeochannels appear as fragmented or discontinuous segments, indicating historical episodes of avulsion, burial by alluvial or coastal sediments, or possible anthropogenic modification through agricultural or developmental activities. The overall spatial pattern and morphological traits of these relict channels correspond with documented fluvial dynamics of the Holocene and Late Pleistocene epochs, suggesting that the basin has experienced significant hydrological and sedimentary evolution over time. The integration of these palaeo-geomorphological features with spectral and topographic indicators reinforces the interpretation of an intricate network of ancient fluvial systems that have shaped the landscape of Kadaladi Taluk.

### Discussion

The identification and delineation of palaeochannels within the Gundar River Basin of Kadaladi Taluk, through the integration of remote sensing and GIS methods, coincides with a developing field of research that utilizes multifactor geospatial analysis to understand subsurface fluvial design. The study's findings are consistent with



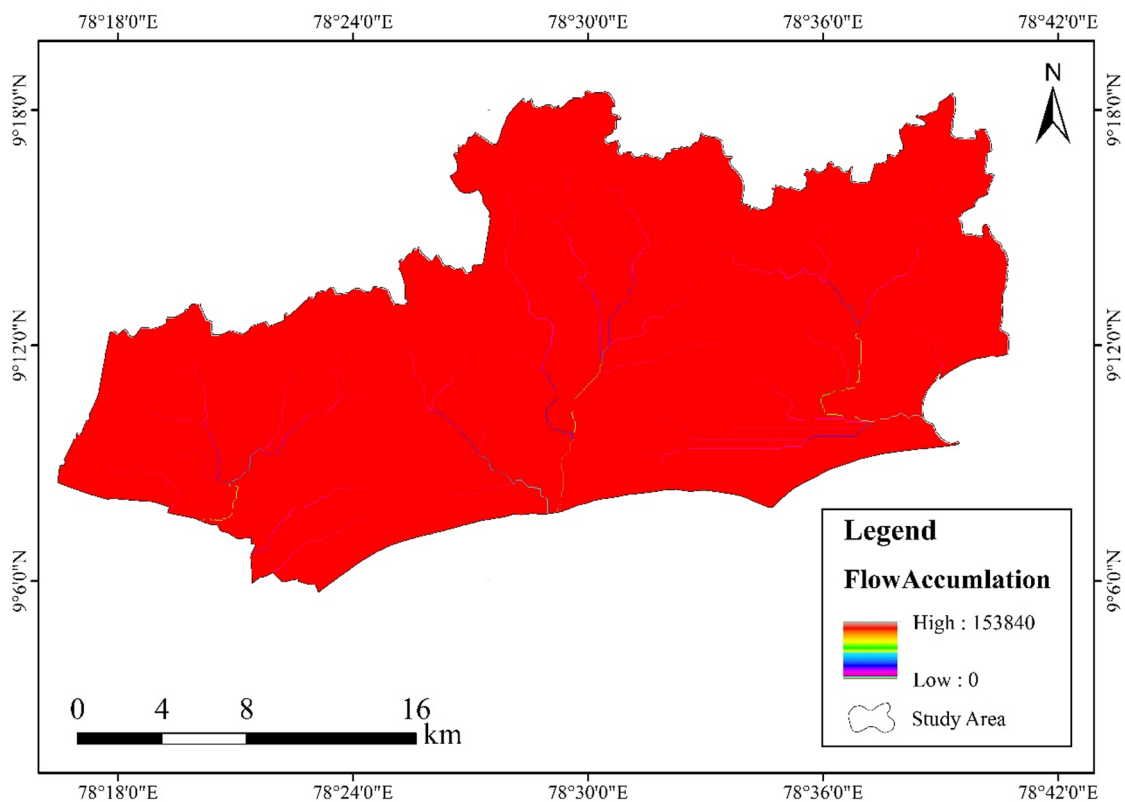
**Fig. 6.** Flow direction map using the D8 model. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

similar discoveries from recent palaeochannel investigations in other river basins around India, particularly the identification of sinuous, meandering relict channels running northwest to southeast, characterized by significant spectral and topographic conditions. For instance, Sajinkumar et al. conducted a study on the Periyar River Basin in Kerala using a combination of remote sensing and electrical resistivity surveys. Their analysis delineated paleochannels in areas with low slopes, high TWI, and concave curvature patterns, parameters also central to the Gundar Basin's detection framework. The resemblance in terrain characteristics and the application of fuzzy logic-based integration for identifying potential fluvial traces underscore the repeatability and reliability of the methods employed in this study.

Similarly, the work by Abhinaba et al. around Talakad in the Cauvery River Basin adopted remote sensing and geophysical methods to identify buried channels. Their research highlighted the role of high-resolution DEMs and spectral indicators in uncovering palaeo fluvial systems hidden beneath agricultural land and alluvial cover. The Gundar Basin analysis corroborated these results through the integration of FCC, NDWI, and NDMI indicators, which revealed moisture-retentive features and buried meanders beneath current land-use surfaces. In the alluvial plains of Haryana, Gupta et al. and Kumar et al. used integrated geophysical tools, including resistivity imaging and drilling, to trace the ancient Saraswati River channel. These studies reported linear, high-moisture corridors associated with high NDWI values and sediment-filled depression features, which were strongly mirrored in the fuzzy overlay results of the present study. Although our work did not include geophysical surveys, the spectral patterns and terrain morphology support similar inferences about sediment characteristics and hydrological behaviour.

More recently, a 2023 study by Jayaraman and Patel emphasized the link between migrating river systems and palaeochannel development in flood-prone areas. Their findings suggested that low-gradient landscapes, such as the coastal plains of Tamil Nadu, particularly those with a history of past fluvial migration, act as hotspots for relict channel preservation. This perspective directly supports the geomorphological observations in the Gundar Basin, where depositional environments and gentle slopes have facilitated the survival of buried palaeochannels.

The palaeochannel features identified in this study display strong agreement with geomorphic and spectral attributes documented in previous palaeodrainage research. The signatures mapped here closely correspond to those reported by Rathore et al.<sup>36</sup> in the Mendha River catchment and Rafeeqe et al.<sup>37</sup> along palaeoshoreline systems, where relict channels exhibit enhanced moisture retention, concave depressions, and distinctive spectral anomalies, attributes that are likewise observed in the Gundar Basin. The integration of TWI, concave curvature (<-5), flow accumulation, and moisture-sensitive spectral indices parallels the multi-criteria frameworks used



**Fig. 7.** Flow Accumulation map highlighting the areas of maximum and minimum flow accumulation. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

in these earlier studies, reinforcing the robustness of terrain-spectral coupling for palaeochannel detection in low-relief basins.

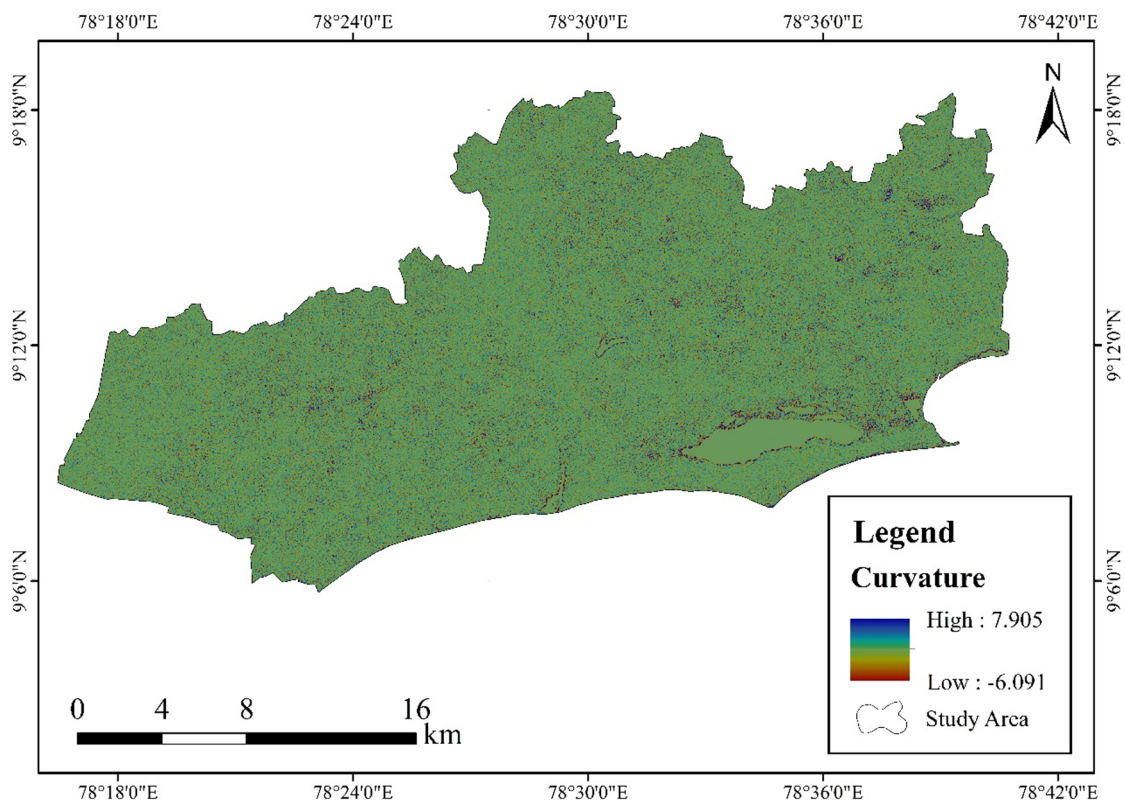
Previous investigations conducted in regions such as Haryana and Kerala have strengthened palaeochannel interpretations through confirming subsurface evidence obtained from electrical resistivity surveys and sedimentological data. The present study is limited by the unavailability of on-site geophysical or drilling data, which restricts direct verification of the subsurface continuity and stratigraphic characteristics of the delineated palaeochannel features.

The lack of field-based confirmation introduces a degree of uncertainty, especially in low-relief coastal environments where subtle topographic and spectral variations can arise from multiple geomorphic processes. Temporal variability in surface moisture and vegetation conditions, along with the spatial resolution limits inherent to medium-resolution satellite sensors such as Landsat-9 and Sentinel-2, may influence the sharpness and positional accuracy of certain mapped features. These factors together highlight the need for careful interpretation of palaeochannel boundaries derived exclusively from spectral and terrain-based indicators.

The spatial consistency of the identified palaeochannel networks and their systematic alignment with regional drainage trends, terrain gradients, and moisture accumulation zones provide integrity to the applied fuzzy overlay modelling approach. The consistency of the mapped patterns with well-documented palaeochannel behaviour observed in comparable fluvial basins across India provides indirect validation of the results. Even in the absence of direct geophysical measurements, the agreement between the inferred palaeochannel corridors and established geomorphological principles lends support to the interpretative strength of the analysis.

Future research should focus on integrating vertical electrical sounding, ground-penetrating radar, or targeted borehole investigations to establish subsurface continuity and lithological correspondence with the remotely sensed palaeochannel features. Such integration would enable quantitative validation of the model outputs and significantly enhance confidence in the spatial predictions generated through remote sensing and GIS-based methods.

The present study demonstrates that the combined application of DEM-derived terrain parameters, multispectral indices, and fuzzy logic modelling constitutes a systematic, non-invasive, and reproducible framework for palaeochannel detection in coastal and semi-arid settings. The methodological consistency and convergence of results with findings from recent basin-scale studies across India indicate the reliability of this approach for preliminary groundwater exploration and basin-scale geomorphological assessment. With increasing pressure on groundwater resources, the proposed framework offers a scalable and transferable tool for regional paleohydrological investigations, while clearly delineating the scope for future subsurface validation.



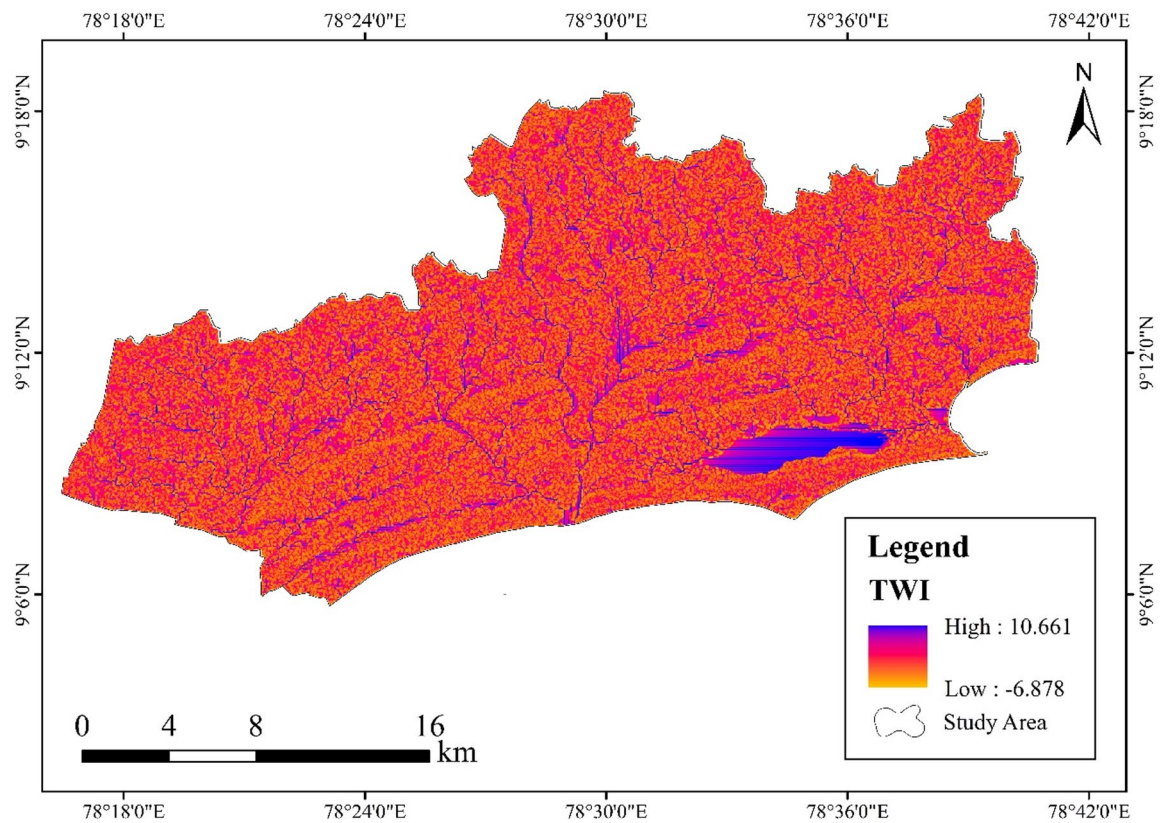
**Fig. 8.** Curvature map deciphering the concave, convex, and flat surfaces of the study area. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

## Conclusion

This study employs an integrated approach that combines advanced fuzzy overlay techniques, Landsat-9-based spectral indices, and terrain parameters derived from the ASTER GDEM to provide a reliable and comprehensive geospatial analysis for defining palaeochannel networks within the Gundar River Basin of Kadaladi Taluk. The study successfully identified several relict fluvial features that primarily trend northwest to southeast, reflecting the area's geomorphological nature in relation to the Bay of Bengal. These remnant channels are further supported by consistent vegetation and moisture anomalies, as indicated by NDVI values (0.35–0.50), NDWI (>0.25), and NDMI (0.30–0.41). These geomorphic expressions are interpreted as low slopes (<3°), concave curvature (<-5), high TWI (>15), and elevated flow accumulation (>2,000 units). The composite interpretations derived from FCC and SWIR-FCC images highlighted sinuous linear features and reflectance contrasts, confirming the presence of moisture-retaining clay-rich sediments characteristic of buried palaeochannel zones. The fuzzy logic integration ( $\gamma=0.8$ ) enhanced spatial accuracy and interpretive reliability, with nearly 18.3% of the basin classified as having high palaeochannel potential. These zones were predominantly concentrated in the central and south-eastern sectors of the study area and were consistent across terrain and spectral indicators, suggesting their suitability for hydrogeological investigations.

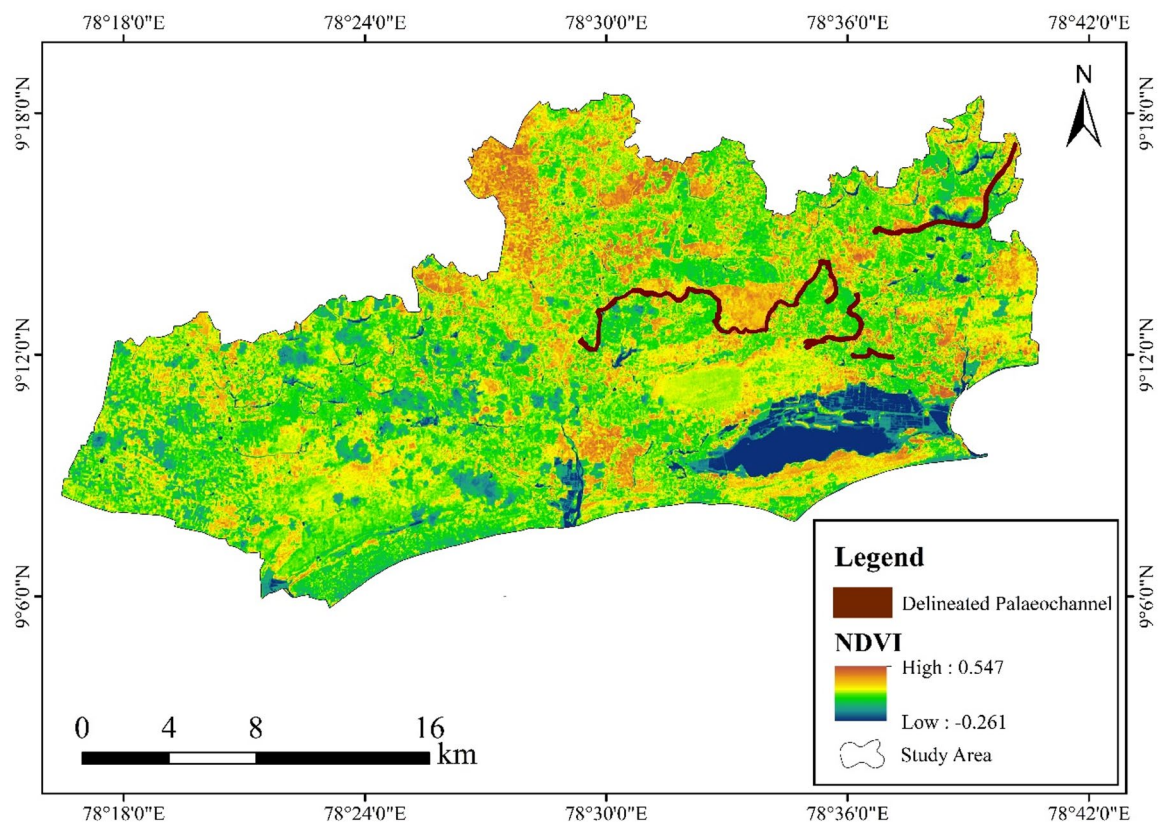
Comparative analysis with recent studies across Indian River basins, such as those conducted in the Periyar River Basin, Talakad (Cauvery Basin), and the Saraswati palaeochannel region of Haryana, demonstrates that the geospatial indicators and geomorphometric features used in this study are both transferable and regionally validated. The results of the current investigation, which lacked geophysical and borehole confirmation, are consistent with known subsurface findings in these areas, confirming the effectiveness of the non-invasive remote sensing and GIS-based method for palaeochannel discovery. The palaeochannel holds significant implications not only for reconstructing the palaeohydrology and fluvial evolution of the Gundar Basin but also for future groundwater exploration and land-use planning. Given that many of these relict channels exhibit high moisture retention and support vegetation, they could act as shallow aquifer recharge zones or guide the planning of artificial recharge structures in water-stressed environments. Moreover, their meandering and discontinuous patterns suggest a history of sedimentation, avulsion, and anthropogenic transformation that merits further sedimentological and chronological exploration.

The study's limitations, including its dependency on remotely sensed data, seasonal variability in spectral indices, and lack of field validation, highlight areas for methodological improvement. To establish chronological frameworks for the identified palaeochannel features, future research should utilize Vertical Electrical Sounding (VES), Ground Penetrating Radar (GPR), and sediment coring to collect ground-based remote sensing outputs. Furthermore, extending the investigation to other sub-basins may uncover interrelated palaeochannel systems,

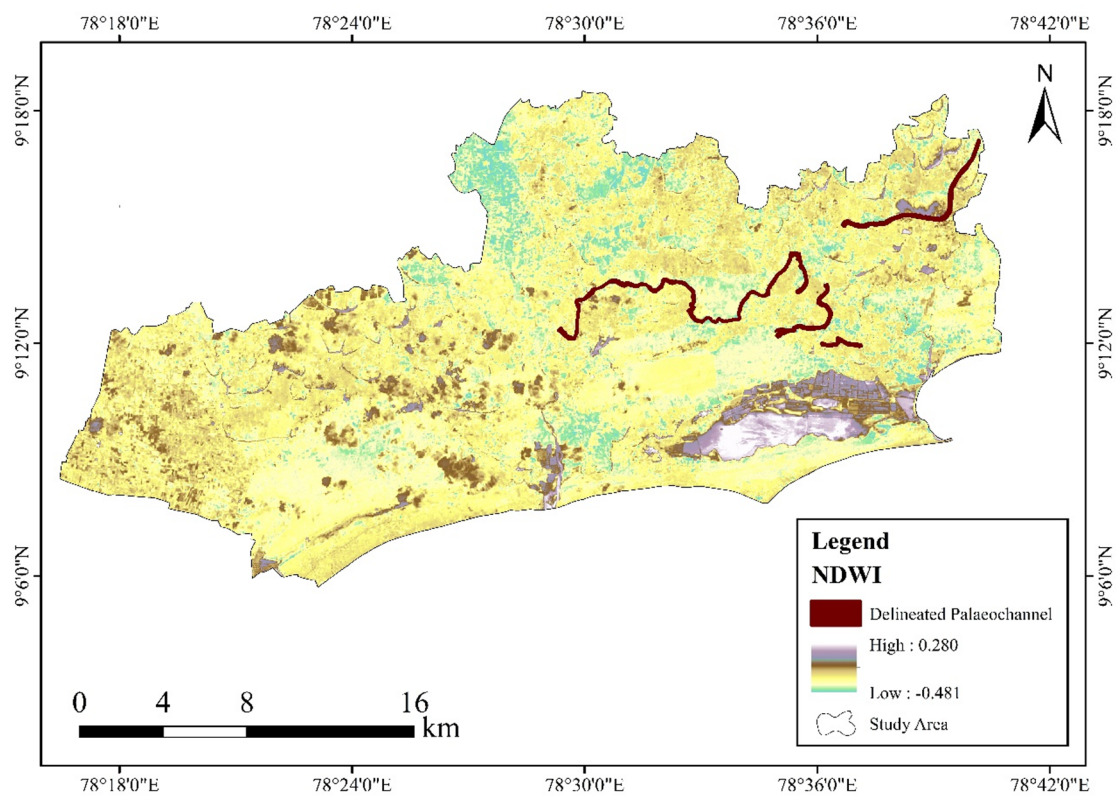


**Fig. 9.** Topographic Wetness Index (TWI) map illustrating spatial variability in surface wetness potential. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

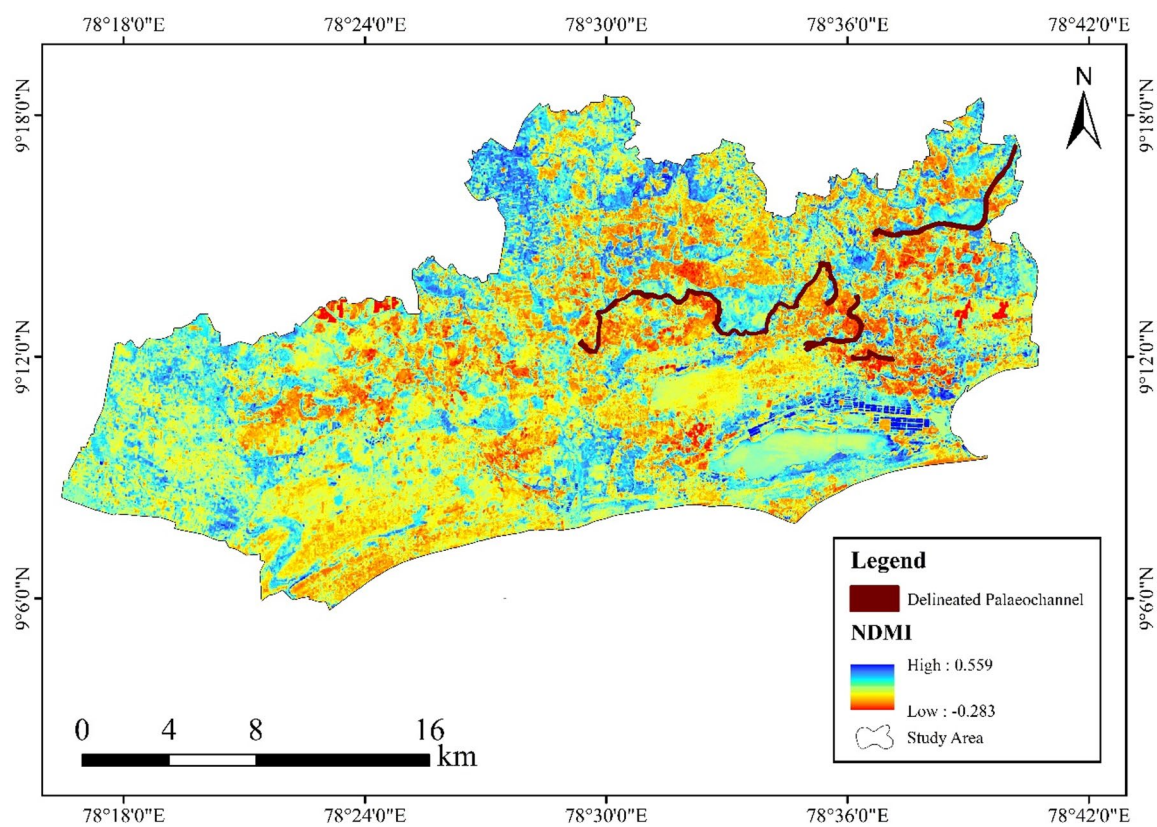
which would advance our knowledge of the development of regional drainage. In conclusion, this study offers a reliable and replicable framework for palaeochannel delineation in coastal and semi-arid terrains. It contributes to the broader field of fluvial geomorphology and demonstrates how complex geospatial analysis can enhance our understanding of the dynamics of rivers in the past, the configurations of landforms today, and the planning of groundwater resources in southern India for the future.



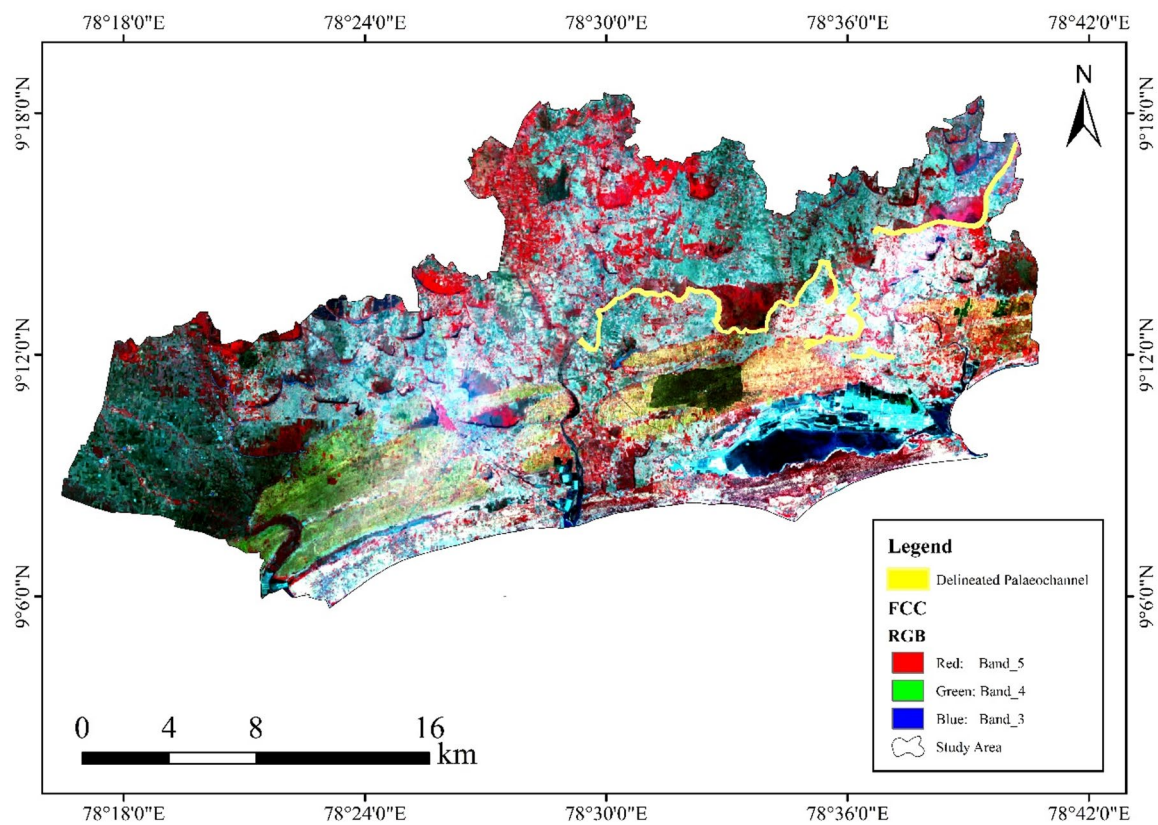
**Fig. 10.** Normalized Difference Vegetation Index (NDVI) Map. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).



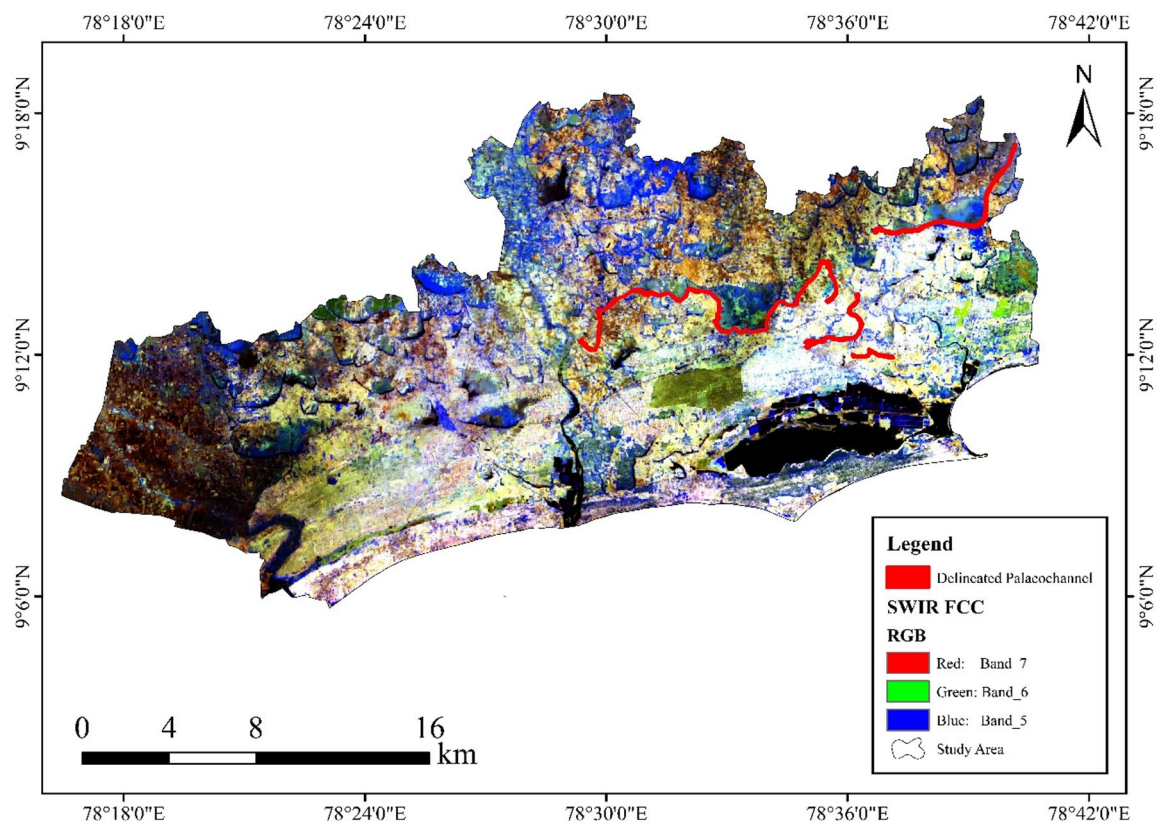
**Fig. 11.** Normalized Difference Water Index (NDWI) Map. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).



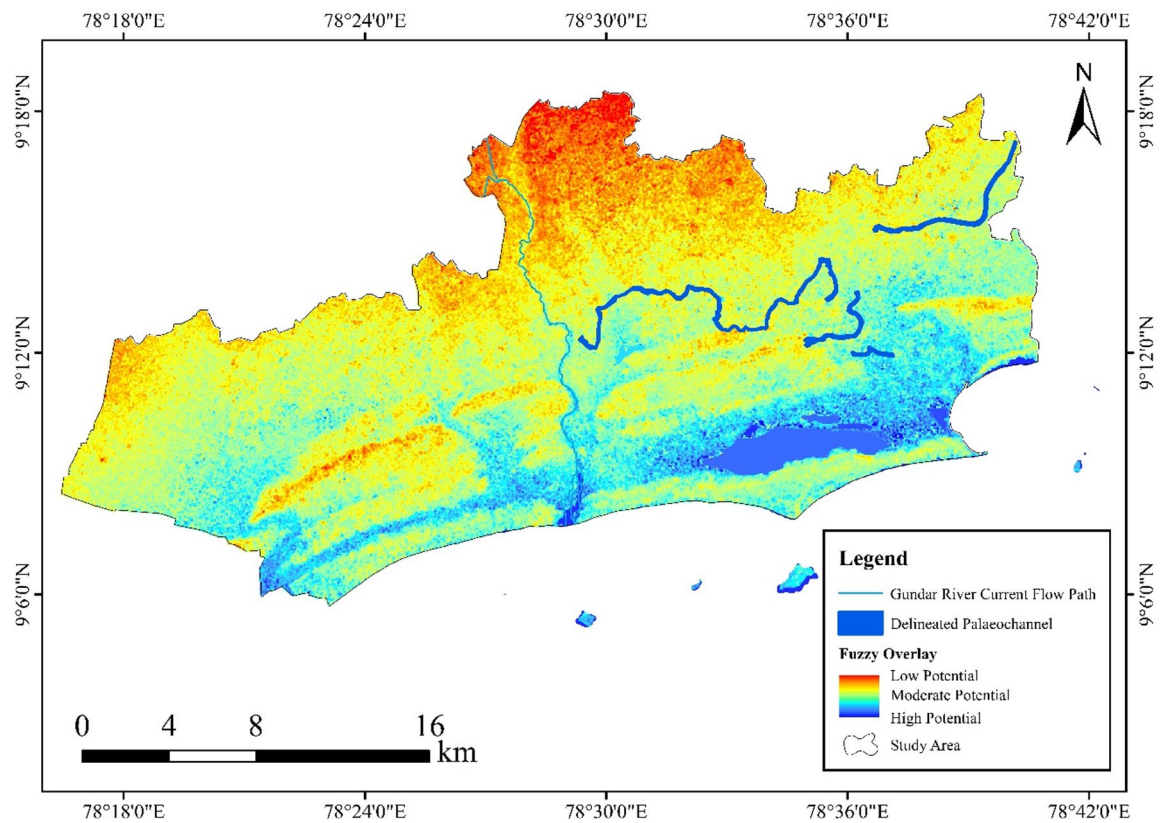
**Fig. 12.** Normalized Difference Moisture Index (NDMI) Map. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).



**Fig. 13.** False colour composite map used for surface feature analysis in the study area. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).



**Fig. 14.** Short-wave infrared false-color composite map highlighting moisture and vegetation variability. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).



**Fig. 15.** Fuzzy overlay analysis for groundwater potential zonation. This figure was prepared using ArcGIS Desktop 10.1 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). The shapefile used in the figure was obtained from the Survey of India (<https://surveyofindia.gov.in/>).

## Data availability

The data that support the findings of this study are available on request from the corresponding author.

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### Author contributions

M. Seeththa Sankar Narayanan : Conceptualization, Methodology, Formal analysis, Investigation, Data curation, and Writing – original draft; V. Stephen Pitchaimani : Supervision, Resources, Software, Validation, and Writing – review & editing. M. Sivakumar : Data curation, Validation, Writing – review & editing; T. Dinesh Kumar : Data curation and Visualization. Shankar Karuppannan : Writing – review & editing; R. J. Jerin Joe : Methodology. All authors have read and agreed to the final version of the manuscript.

### Declarations

#### Competing interests

The authors declare no competing interests.

#### Additional information

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