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Spatio-temporal analysis of Thoubal River morphodynamics and its relationship with land use/land cover changes, flood hazards and anthropogenic activities, Manipur, India

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Abstract

River systems are dynamic geomorphic environments whose channel form and behavior respond to variations in discharge, sediment supply, rainfall, vegetation cover, land-use change and human intervention. The Thoubal River, one of the important fluvial systems of Manipur, has experienced considerable changes in channel configuration and surrounding land use during recent decades. The present study investigates the spatio-temporal evolution of the Thoubal River between 1990 and 2024 and evaluates its relationship with Land Use/Land Cover (LULC) transformation, anthropogenic pressure, rainfall variability and flood hazards using remote sensing, Geographic Information System (GIS), digital elevation modelling and field verification.

Multi-temporal Landsat imagery for 1990, 2000, 2010, 2020 and 2024 was analyzed for LULC classification and change detection. River-channel migration and erosion/deposition were assessed using multi-temporal channel boundaries and the Digital Shoreline Analysis System (DSAS) approach adapted to fluvial channel analysis. Channel length, mean width, sinuosity, braiding index and drainage density were calculated to quantify morphological change. A weighted multi-criteria approach incorporating rainfall, slope, elevation, and distance from the river, drainage density, LULC, and landform was used to prepare the 2024 flood hazard map. Anthropogenic pressure was evaluated using built-up expansion and spatial information on sand mining, urbanization, agricultural expansion, embankments, roads, bridges and waste disposal.

The results indicate substantial morphological transformation of the Thoubal River. Total channel length increased from 77.64 km in 1990 to 79.13 km in 2024, while mean channel width increased from 162.3 to 228.7 m. Sinuosity increased from 1.36 to 1.72 and the braiding index increased from 0.28 to 0.49, indicating increasing channel complexity and lateral in stability. Built-up land expanded from 6,768 ha in 1990 to 20,543 ha in 2024, whereas agricultural land and forest cover declined. Approximately 66.13% of the analyzed area remained relatively stable with respect to erosion/deposition, while the remaining areas show substantial geomorphic activity. The upper reach recorded an average net migration rate of +1.38 m/year, the middle reach +0.72 m/year, and the lower reach -1.12 m/year. A strong positive relationship was observed between built-up expansion and net channel migration ($r = 0.71$, $p < 0.01$), while built-up area was also strongly correlated with flood hazard ($r = 0.75$, $p < 0.01$). Mean rainfall increased from 1,702 mm during 1990-1999 to 2,146 mm during 2020-2024. The findings demonstrate that natural hydrological forcing and increasing anthropogenic pressure are jointly associated with morphodynamic change and flood vulnerability in the Thoubal River Basin. Integrated river-basin management, riparian-zone protection, regulation of sand mining and encroachment, floodplain zoning and continuous remote-sensing-based monitoring are recommended.

Keywords: Thoubal River, river morphodynamics, channel migration, erosion and deposition, LULC, remote sensing, GIS, flood hazard, anthropogenic pressure, Manipur

Introduction

Rivers are among the most dynamic components of the Earth's surface system. Their channels continuously adjust their plan form, width, depth, sinuosity and sediment distribution in response to variations in discharge, sediment load, valley slope, bank material, vegetation and human intervention.

Changes in river morphology can generate significant environmental and socioeconomic consequences, particularly in densely settled floodplains where agricultural land, roads, bridges and settlements are concentrated along river corridors.

During the last several decades, rapid population growth, urban expansion, agricultural intensification, deforestation, sand extraction, riverbank modification and construction of embankments have altered many river systems throughout India. These anthropogenic activities modify run off generation, sediment availability, bank stability and flood conveyance capacity. At the same time, changes in rainfall intensity and seasonal precipitation associated with climatic variability may amplify the magnitude and frequency of floods.

Remote sensing and GIS provide effective techniques for analysing river dynamics over long periods because historical satellite imagery permits reconstruction of channel positions and surrounding land-use patterns. Multi-temporal Landsat data are particularly useful because of their long temporal coverage and moderate spatial resolution. Integration of satellite-based LULC classification with river channel extraction, GIS-based morphometric analysis and flood hazard modelling provides an effective framework for understanding interactions between environmental change and river dynamics.

The Thoubal River Basin of Manipur represents an important case for such an investigation. The river passes through areas experiencing agricultural development, urbanization and increasing infrastructure pressure. Changes in river channel position and width have implications for agriculture, settlements, roads, bridges, floodplain management and ecological stability. The present study therefore focuses on the spatial and temporal evolution of the Thoubal River from 1990 to 2024 and examines the relationships between river morphodynamics, LULC change, rainfall variability, anthropogenic activities and flood hazards.

Study area

Location and physiographic setting

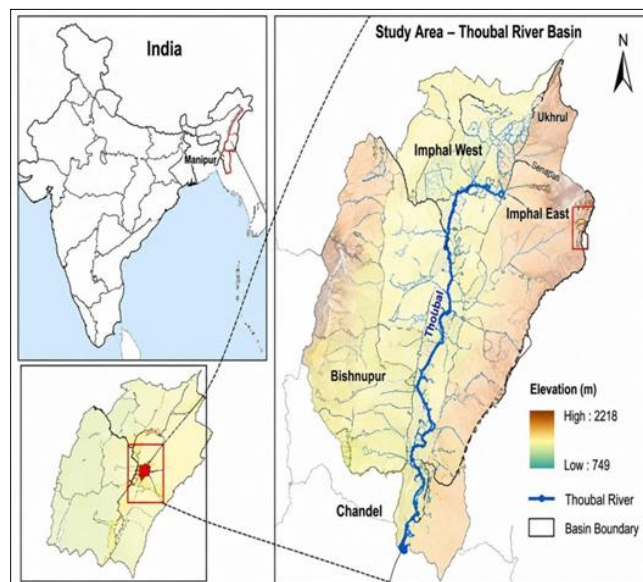


Fig 1: Location map of the Thoubal River Basin, Manipur, India

The Thoubal River Basin is situated in Manipur, northeastern India, and forms an important component of the drainage network of the Manipur Valley. The river drains a heterogeneous landscape comprising upland/hilly terrain, agricultural areas, settlements, forested regions and low-lying floodplains. Figure 1 shows the study-area setting and basin extent. The study-area map indicates an elevation range of approximately 749-2,218 m, reflecting considerable topographic variability within the basin. The river flows through the Thoubal region and ultimately contributes to the lowland drainage system associated with Loktak Lake.

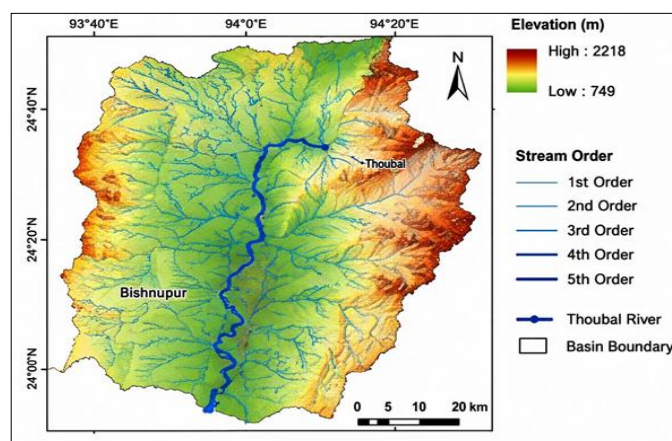


Fig 2: Digital elevation model and drainage network of the Thoubal River Basin

The basin contains both relatively stable upstream areas and intensively modified middle and downstream reaches. The floodplain has undergone increasing agricultural and urban development, while sand mining, embankment construction, roads, bridges and settlement expansion have locally modified the river corridor. The DEM illustrates the marked elevation gradient across the basin and the organization of the drainage network. Higher terrain occurs around the basin

margins, whereas lower elevations are concentrated along the main valley and downstream areas, providing the topographic framework for river flow and flood susceptibility. The combination of monsoonal rainfall, relatively steep upstream terrain, sediment availability, floodplain development and increasing anthropogenic pressure makes the Thoubal River a suitable setting for investigating contemporary fluvial morphodynamics.

Materials and Methods

Data sources

The overall analytical workflow is summarized in Figure 3.

The analysis was based mainly on multi-temporal satellite imagery, DEM data, topographic information, rainfall records and field observations.

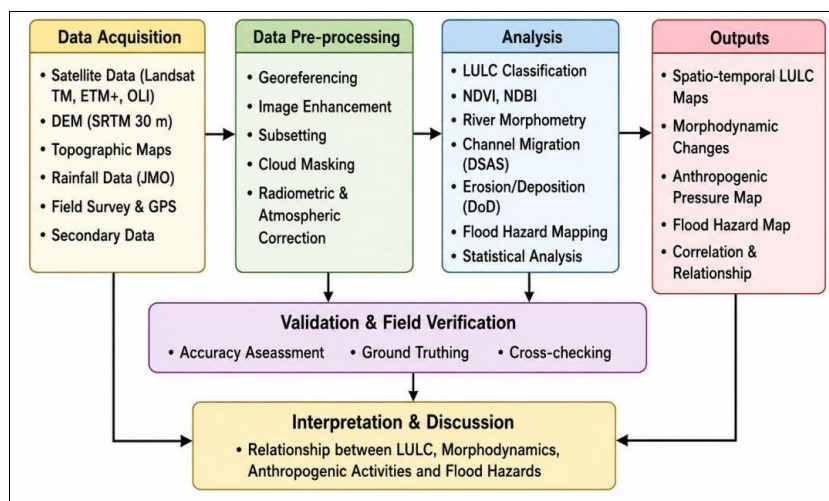


Fig 3: Research methodology adopted for the study.

Table 1: Satellite data and ancillary datasets

Dataset	Source	Year/Period	Spatial Resolution	Major Use
Landsat 5TM	USGS	1990,2000	30m	LULC and change detection
Landsat 7ETM+	USGS	2010	30m	LULC and NDBI
Landsat 8 OLI/TIRS	USGS	2020	30m	LULC and NDBI
Landsat 9 OLI/TIRS	USGS	2024	30m	LULC and NDBI
SRTMDEM	USGS	-	30m	Slope, drainage and morphometry
SOI Topo sheets	Survey of India	-	1:50,000	Base map and drainage verification
Rainfall data	IMD, Manipur	1990-2024	Daily	Rainfall and flood analysis
Field survey/GPS	Primary	2024	-	Ground verification

Cloud-free or relatively low-cloud satellite scenes representing comparable seasonal conditions were selected, as far as possible, to reduce seasonal effects on LULC classification and channel extraction.

Image preprocessing

Satellite images were subjected to:

- Geometric correction/geo referencing;
- Radiometric and atmospheric correction;
- Image enhancement;
- Sub setting to the study boundary;
- Cloud and cloud-shadow masking where required; and
- Band preparation for classification and spectral-index calculation.

The images were projected into a common coordinate reference system to ensure accurate overlay and change detection.

LULC classification

A supervised classification approach using the Random Forest algorithm (Breiman, 2001) [2] was applied to classify the basin into the following principal land-use/land-cover classes:

1. Waterbody
2. Forest
3. Agriculture
4. Built-up
5. Barrenland
6. Others

Training samples were developed using satellite-image interpretation, ancillary maps and field observations. Post-classification smoothing and editing were performed to remove isolated pixels and improve thematic consistency.

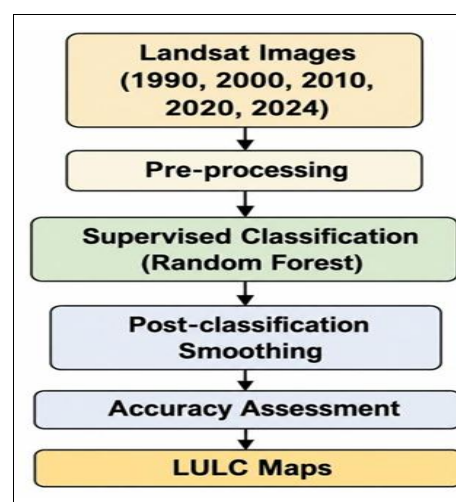


Fig 4: LULC classification and accuracy-assessment framework.

Figure 4 shows the classification framework shows the sequence from multi-temporal Landsat imagery through preprocessing and supervised Random Forest classification to post-classification smoothing, accuracy assessment and final LULC maps. This workflow provides the basis for the subsequent LULC change analysis.

Classification accuracy

The classification results showed overall accuracies ranging from 87.32% to 90.76%, with corresponding kappa coefficients of 0.84-0.89.

Table 2: Classification accuracy assessment

Year	Overall Accuracy (%)	Kappa Coefficient	Assessment
1990	87.32	0.84	Good
2000	88.17	0.86	Good
2010	89.25	0.87	Very Good
2020	90.11	0.88	Very Good
2024	90.76	0.89	Very Good

The overall classification accuracies exceed 87%, indicating acceptable thematic performance for the subsequent change-detection analysis (Congalton & Green, 2019) ^[4].

LULC change analysis

The LULC transition pattern is illustrated in Figure 5. The LULC results demonstrate substantial transformation of the Thoubal River Basin during 1990-2024.

Table 3: LULC statistics

LULC class	1990(ha)	2000(ha)	2010(ha)	2020(ha)	2024(ha)
Waterbody	9,128	8,756	8,112	7,169	6,042
Forest	12,246	11,587	10,432	9,256	8,745
Agriculture	54,812	53,214	51,236	50,312	49,281
Built-up	6,768	8,946	12,875	16,984	20,543
Barrenland	3,214	2,965	2,614	2,421	2,118
Others	1,366	2,233	2,472	2,579	2,252

The most prominent change is the expansion of built-up land. Built-up area increased from 6,768 ha in 1990 to 20,543 ha in 2024, representing an increase of approximately 203.6%. Because the classified-area totals vary among observation years, the reported class areas should be interpreted as year-specific classified areas rather than as a perfectly constant-area accounting framework.

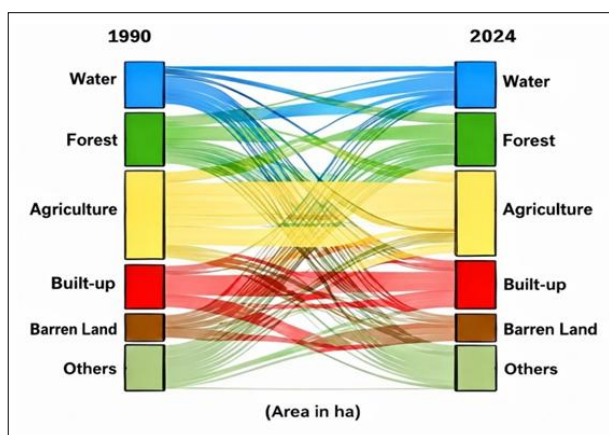


Fig 5: LULC transition during 1990-2024.

The transition diagram Figure 5 illustrates the persistence and conversion of the principal LULC classes between 1990 and 2024. The most prominent transformation is the expansion of built-up land, accompanied by reductions in forest and agricultural areas, indicating progressive landscape modification within the basin.

In contrast, forest cover declined from 12,246 ha to 8,745 ha, a reduction of approximately 28.6%. Agricultural land

also declined from 54,812 ha to 49,281 ha.

The decline in forest and agricultural areas and simultaneous expansion of built-up land indicate progressive landscape transformation. Such changes are particularly important for river behavior because impervious surfaces increase surface runoff and can reduce infiltration.

Built-up expansion and NDBI analysis

The Normalized Difference Built-up Index (NDBI) was used to identify spatial patterns of built-up expansion.

The spatial pattern of built-up expansion is shown in Figure 6. The NDBI results demonstrate a progressive concentration of built-up surfaces along major transportation corridors, settlements and river-adjacent areas. The spatial expansion is particularly evident between 2000 and 2024.

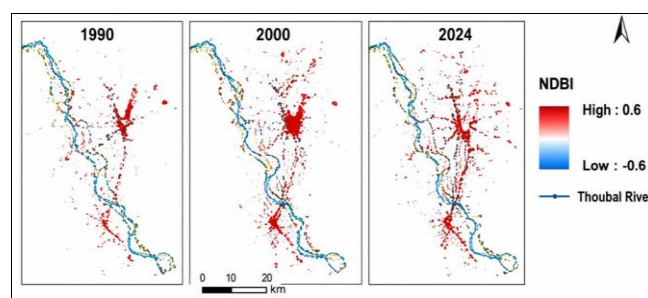


Fig 6: Spatial expansion of built-up areas based on NDBI, 1990-2024.

The NDBI maps (Fig. 6) show progressive concentration and expansion of built-up surfaces through the study period. Development is especially evident around settlements and transportation corridors, including areas close to the river, highlighting increasing anthropogenic pressure on the river corridor and floodplain.

The expansion of impervious surfaces may increase:

- Peak surface run off;
- Drainage density;
- Flood plain inundation;
- Sediment transport;
- Bank erosion;
- Pressure for river bank encroachment; and
- Exposure of settlements and infrastructure to floods.

The spatial coincidence between built-up expansion and zones of channel migration suggests an important anthropogenic association with contemporary river dynamics; however, the observed relationships should not be interpreted as proof of direct causation.

River-channel extraction and morphometric analysis

Figure 7 presents the extracted multi-temporal channel positions. Multi-temporal channel boundaries were extracted from Landsat imagery for 1990, 2000, 2010, 2020 and 2024.

The channel network was analyzed using GIS to calculate:

- Total channel length;
- Mean channel width;
- Sinuosity;
- Braiding index;
- Stream order; and
- Drainage density.

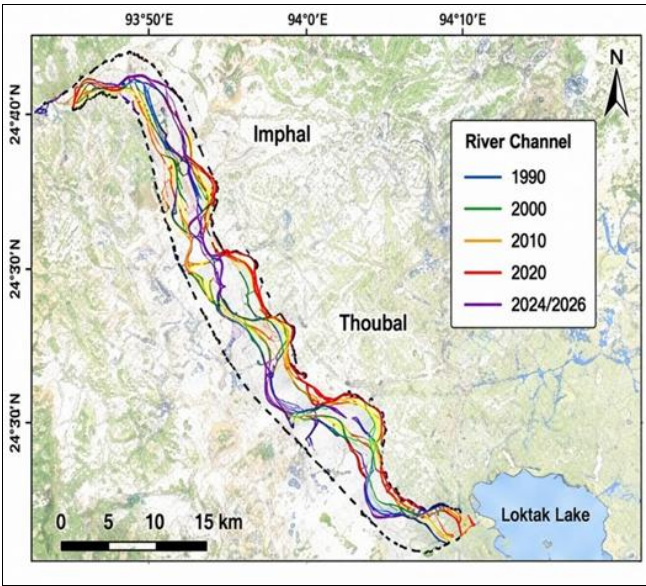


Fig 7: Multi-temporal evolution of the Thoubal river channel, 1990-2024.

Table 4: River-channel morphometric parameters

Parameter	1990	2000	2010	2020	2024
Total length (km)	77.64	77.93	78.21	78.68	79.13
Mean width (m)	162.3	173.8	191.6	214.5	228.7
Sinuosity	1.36	1.42	1.53	1.63	1.72
Braiding index	0.28	0.31	0.36	0.43	0.49
Maximum stream order	5	5	5	5	5
Drain age density (km/km ²)	1.42	1.43	1.44	1.46	1.47

Figure 6 summarizes longitudinal channel-width variation. The results reveal progressive morphological adjustment of the river.

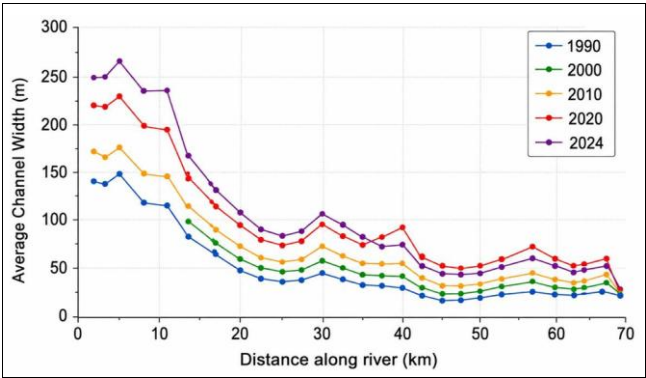


Fig 8: Variation in mean channel width along the Thoubal River, 1990-2024.

The longitudinal profiles (fig 8) show that channel width varies substantially along the river and generally increases in the later observation years. The widening is most pronounced in several upstream and middle-reach sections, while narrower reaches occur farther downstream. Mean channel width increased by approximately 41%, from 162.3 m in 1990 to 228.7 m in 2024. This substantial increase indicates widening of the active channel and/or greater representation of water and exposed channel surfaces in the later satellite scenes.

Sinuosity increased from 1.36 to 1.72, demonstrating increasing plan form irregularity and lateral development. The braiding index increased from 0.28 to 0.49, suggesting greater channel segmentation and development of multiple flow paths. Drainage density increased moderately from 1.42 to 1.47 km/km².

Multi-temporal channel migration

The channel positions for 1990, 2000, 2010, 2020 and 2024 were superimposed to identify zones of lateral migration. The results indicate that channel movement is spatially heterogeneous. Some reaches exhibit substantial lateral displacement, whereas other sections remain relatively stable.

Table 5: Erosion/deposition statistics, 1990-2024

Category	Area(ha)	Percentage of to talarea
High erosion (>30m)	2,184	2.43
Mode rate erosion(10-30m)	4,762	5.31
Slight erosion (5-10 m)	6,213	6.92
Stable (-5to+5m)	59,426	66.13
Slight deposition (5-10m)	7,942	8.84
Mode rate deposition (10-30m)	6,518	7.25
High deposition (>30 m)	2,754	3.04

The spatial pattern of erosion and deposition is shown in Figure 9. Approximately two-thirds of the basin remained within the stable category, whereas considerable portions experienced erosion or deposition.

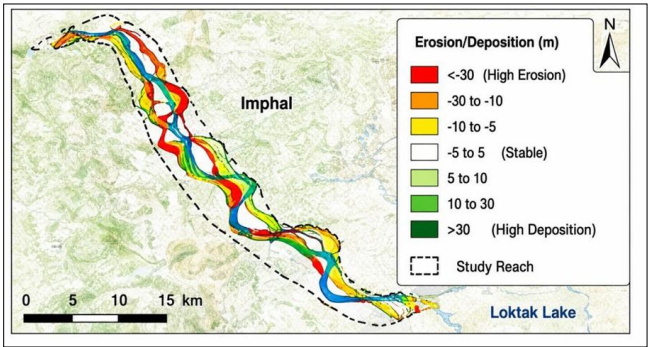


Fig 9: River bank migration and erosion/deposition, 1990-2024.

The map (Fig 9) identifies spatially variable zones of erosion, deposition and relative stability along the river corridor. Erosion and deposition occur on opposing and adjacent channel margins, demonstrating active bank adjustment and sediment redistribution, while substantial portions remain comparatively stable. The total erosion-affected classes account for approximately 14.66%, while deposition classes account for approximately 19.13%. This indicates that deposition occupies a slightly larger area than erosion, although local erosion intensity may be substantial along individual banks.

Channel migration rate by reach

For detailed analysis, the river was divided into three reaches:

- Upper reach: 0-20 km
- Middle reach: 20-50km
- Lower reach: 50-79 km

Table 6: Channel migration rate by reach, 1990-2024

Reach	Length(km)	Average net migration rate(m/year)	Dominant process
Upper (0-20km)	20.0	+1.38	Deposition
Middle(20-50km)	30.0	+0.72	Mixed
Lower(50-79km)	29.0	-1.12	Erosion
Overall	79.0	-0.21	Slight erosion

The upper reach shows a positive migration rate of approximately 1.38 m/year and is dominated by depositional processes. The middle reach exhibits moderate migration with mixed erosion and deposition. The lower reach records

the highest erosional tendency, with an average net migration rate of approximately -1.12 m/year. The reach-level results indicate strong spatial heterogeneity, with a depositional tendency in the upper reach and a stronger erosional tendency in the lower reach. Because a basin-scale migration rate cannot be independently reproduced from the reach-level values alone, no basin-wide migration rate is reported here.

Sinuosity and braiding

Figure 10 shows the temporal increase in sinuosity and braiding. The increasing sinuosity and braiding index provide important evidence of channel instability.

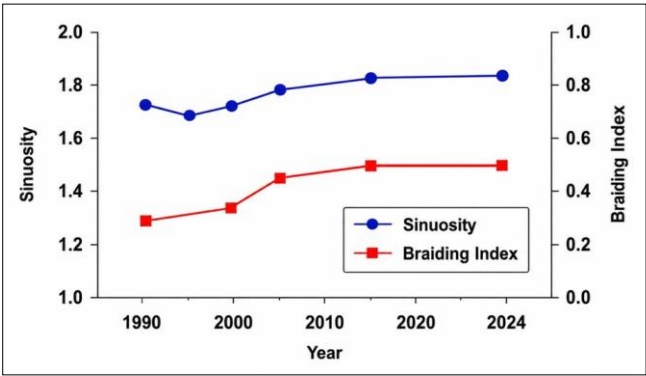


Fig 10: Temporal variation in sinuosity and braiding index, 1990-2024.

Sinuosity increased from 1.36 in 1990 to 1.72 in 2024. This increase suggests enhanced lateral migration and development of bends. Similarly, the braiding index increased from 0.28 to 0.49. Increased braiding may result from changes in sediment supply, bank erosion, channel widening, variable discharge and local human disturbances. The simultaneous increase in sinuosity, braiding and

channel width indicates that the Thoubal River has become morphologically more complex during the study period.

Anthropogenic activities

The spatial distribution of anthropogenic pressure is shown in Figure 11. The 2024 anthropogenic-pressure assessment identified several activities affecting the river system.

Table 7: Major anthropogenic activities and their impacts

Activity	Major locations	Intensity	Major impact
Sand mining	Middle and lower reaches	High	Channel incision and bank erosion
Urban isation	Basin-edge and settlement areas	High	Increased runoff and flood risk
Agricultural expansion	Basin fringe	Moderate	Land clearing and sediment yield
Embankments/check dams	Middle and lower reaches	Moderate	Flow alteration and siltation
Road sand bridges	Through out the basin	Moderate	Obstruction and local erosion
Waste disposal	Near urban areas	High	Water-quality degradation

Sand mining is particularly important because removal of channel sediment can alter the sediment budget and destabilize riverbanks. Urbanisation increases impervious

surfaces and run off, while roads and bridges can locally constrict flow and produce scour.

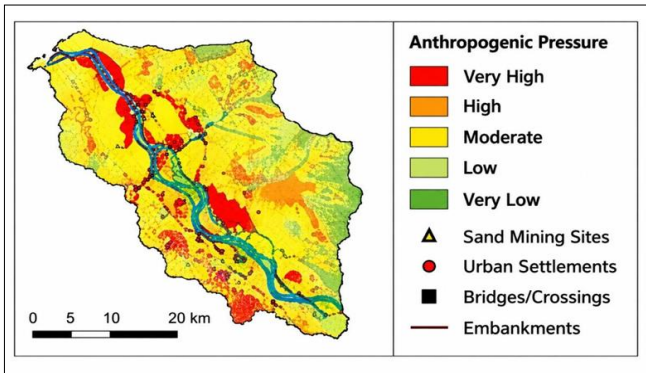


Fig 11: Spatial distribution of anthropogenic pressure in 2024.

Embankments may protect selected settlements but can also modify natural channel-floodplain connectivity and alter sediment deposition patterns.

Flood-hazard assessment

Flood hazard was assessed through a weighted multi-criteria GIS frame work. The selected parameters and their weights were:

Table 8: Flood-hazard evaluation criteria and weights

Parameter	Weight (%)
Rainfall	20
Slope	15
Elevation	15
Distanceto river	20
Drainage density	10
LULC/Built-up	10
Landform	10
Total	100

The flood hazard index can be expressed conceptually as:

$$FHI = \sum (W_i R_i)$$

Where:

- (FHI) =Flood Hazard Index,
- (W_i)=weight assigned to parameter(i),
- (R_i)=reclassified/ranked value of parameter(i).

The resulting flood hazard map categorized the basin into very low, low, moderate, high and very high hazard zones.

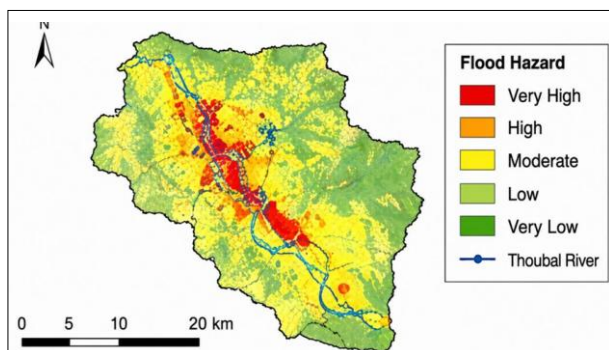


Fig 12: Flood-hazard map of the Thoubal River Basin, 2024.

The flood-hazard map (Fig 12) classifies the basin into very-low to very-high relative hazard zones. High and very-high hazard areas are concentrated mainly along low-lying floodplains and close to the river, where gentle slopes, drainage characteristics and developed land increase exposure to flooding.

Rainfall trend

Rain fall data for 1990-2024 indicate an increasing trend in mean annual rainfall.

Table 9: Rainfall trend

Period	Mean annual rainfall (mm)	Change relative to baseline
1990-1999	1,702	-
2000-2009	1,862	+9.40%
2010-2019	1,984	+16.58%
2020-2024	2,146	+21.67%

Mean annual rainfall increased from 1,702mm during1990-1999 to 2,146mm during2020-2024.

This increase is important for river morphodynamics because greater rainfall can generate higher runoff, particularly when associated with increasing impervious surfaces and declining vegetation cover. However, rainfall alone cannot explain channel change. River morphology responds to the combined influence of discharge, sediment supply, bank material, vegetation, floodplain confinement and human modification.

Relationship between LULC, rain fall and river morphodynamics

Figure 13 illustrates the relationship between built-up expansion and channel migration. Statistical analysis indicates significant relationships among several environmental variables.

Table 10: Correlation between LULC, rainfall and river morphology

Variables	Correlation coefficient (r)	Significance
Built-up area vs. net migration rate	0.71	$p < 0.01$
Rainfall vs. mean channel width	0.64	$p < 0.01$
Built-up area vs. flood-hazard index	0.75	$p < 0.01$

The correlation coefficient of 0.71 between built-up area and net channel migration indicates a strong positive association. This suggests that increasing urban development is closely associated with increasing channel mobility.

The correlation between rainfall and mean channel width ($r = 0.64$) suggests that increased rainfall may contribute to channel widening through increased runoff and discharge.

Thestrongpositivecorrelationbetweenbuilt-upareaandfloodhazard($r=0.75$) demonstrates the important role of urbanization in increasing flood vulnerability.

The study findings support the importance of conserving forest and riparian vegetation because vegetation can contribute to bank stability and reduced sediment mobilisation. The reported statistical relationships should be interpreted as associations rather than evidence of direct causation

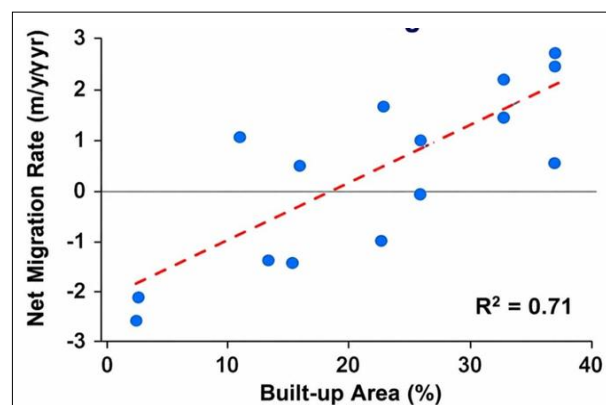


Fig 13: Relationship between LULC change and channel migration.

The scatter plot (Fig 14) indicates a positive association between built-up area and net channel migration, with $R^2 = 0.71$. The relationship supports the interpretation that areas experiencing greater development also tend to show greater

channel mobility, although the statistical association should not be interpreted as proof of direct causation.

Discussion

River morphodynamic evolution

The Thoubal River has undergone substantial morphological adjustment between 1990 and 2024. The increase in channel length, width, sinuosity and braiding index demonstrates that the river has become progressively more laterally complex.

The approximately 41% increase in mean channel width is particularly significant. Channel widening may result from increased peak discharge, bank erosion, sediment redistribution and removal of bank vegetation. Human activities can accelerate these processes by weakening bank resistance and modifying flow.

The increase in sinuosity from 1.36 to 1.72 in dictates progressive lateral development of channel bends. Meander migration can occur naturally, but accelerated migration near settlements and infrastructure represents a significant management concern.

LULC transformation

The most important landscape transformation is the rapid expansion of built-up land. Built-up area increased more than three fold in relative terms between 1990 and 2024, while forest cover declined.

Urbanisation has several consequences for river systems:

1. Increased impervious surface area;
2. Reduced infiltration;
3. Increased surface run off;
4. Rapid delivery of storm water to drainage channels;
5. Increased flood peaks;
6. Increased pressure on floodplains; and
7. Increased exposure of people and infrastructure to river hazards.

Thus, LULC transformation provides an important anthropogenic context for interpreting the observed river changes.

Erosion and Deposition

The erosion/deposition analysis shows that the Thoubal River is characterized by spatially variable geomorphic activity.

The lower reach has the strongest erosional tendency. This may be associated with increased flow concentration, channel adjustment, bank-material properties and human interventions.

Conversely, depositional zones occur where velocity decreases flow and sediment is stored within the floodplain or channel. The coexistence of erosion and deposition demonstrates that the river is responding dynamically rather than undergoing uniform channel migration.

Role of anthropogenic activities

Sand mining is likely to be particularly important in modifying local channel morphology. Excessive sediment extraction can produce bed degradation, local channel incision and bank instability. Urban development and infrastructure construction further constrain natural channel migration. Bridges and embankments can modify flow velocity and sediment transport, producing local scour and deposition.

Agricultural expansion may increase sediment delivery where vegetation is removed, while waste disposal near urban areas contributes to water-quality degradation.

Rainfall and flood hazard

The increasing rain fall values shown in the study data set coincide with increasing channel width and flood vulnerability. The relationship between rainfall and channel width is statistically positive.

Nevertheless, flood hazard is controlled by multiple factors. Areas with high rainfall may not necessarily experience severe flooding if they have steep slopes, high infiltration or efficient drainage. Conversely, low-lying areas closet other river can remain highly vulnerable even under moderate rainfall.

The weighted flood hazard approach therefore provides a more realistic representation than rainfall alone.

Conceptual model of thoubal river morphodynamics

The results support a conceptual model in which natural and anthropogenic factors interact to control channel evolution.

Major driving factors

Monsoon rainfall → increased runoff → increased discharge
Land-use change → reduced infiltration → increased surface runoff
Deforestation → increased sediment production → increased sediment delivery
Urbanisation → increased impervious surfaces → rapid runoff response
Sand mining → sediment-budget disturbance → channel instability
Embankment sand infrastructure → altered flow → locals scour/deposition

These processes result in:

- Bank erosion;
- Channel migration;
- Channel widening;
- Increased sinuosity;
- Increasing braiding;
- Sediment redistribution; and
- Flood plain inundation.

The ultimate consequences include:

- Flood hazard;
- Agricultural loss;
- Infrastructure damage;
- Settlement exposure; and
- Ecological degradation.

Implications for river-basin management

The findings have important implications for sustainable management of the Thoubal River.

Riparian buffer protection

Vegetated riparian zones should be maintained along vulnerable riverbanks. Riparian vegetation increases bank resistance, reduces erosion and provides ecological habitat.

Regulation of sand mining

Sand extraction should be scientifically regulated, particularly in reaches showing high erosion and channel instability. Extraction should not be permitted in sensitive zones immediately adjacent to unstable banks, bridges and important infrastructure.

Flood plain zoning

High-and very-high-hazard areas should be identified as restricted-development zones. New settlements and critical infrastructure should be discouraged in active floodplains.

Sustainable urban planning

Urban expansion should incorporate:

- Storm water-management systems;
- Permeable surfaces;
- Drainage retention structures;
- Flood-resilient infrastructure; and
- Protection of natural drainage channels.

River bank stabilisation

Bioengineering techniques should be preferred wherever feasible. Stabilisation should be based on detailed hydraulic and geomorphic assessment rather than indiscriminate hard engineering.

Continuous remote-sensing monitoring

Satellite-based monitoring should be repeated at regular intervals to identify:

- New erosion hotspots;
- Channel migration;
- Illegal sandmining;
- Floodplain encroachment;
- Built-up expansion; and
- Changes in riparian vegetation.

Limitations of the study

Although the study provides a comprehensive GIS and remote-sensing framework, several limitations should be recognised.

1. Landsat imagery has a spatial resolution of approximately 30 m, which limits the detection of very small-scale bank changes.
2. Differences in satellite acquisition date and river discharge conditions may introduce uncertainty in channel-width measurements.
3. LULC classification errors can influence subsequent correlation and floodhazard analysis.
4. Anthropogenic activities may not be uniformly represented through the entire study period because detailed historical activity records are limited.
5. Correlation does not establish causation.
6. The floodhazard map is a relative susceptibility model and should not be interpreted as a hydraulic inundation simulation.
7. More detailed validation using high-resolution satellite imagery, UAV surveys, cross-sectional surveys and continuous hydrological measurements would improve the results.
8. The quantitative results should be verified against the original GIS data base and source datasets before final submission.

Conclusions

The present study demonstrates significant spatio-temporal changes in the morphology and environmental setting of the Thoubal River during 1990-2024.

The major conclusions are:

1. The Thoubal River channel length increased from 77.64 km in 1990 to 79.13 km in 2024.

2. Mean channel width increased from 162.3 m to 228.7 m, indicating substantial channel widening.
3. Sinuosity increased from 1.36 to 1.72, demonstrating increasing plan form complexity.
4. The braiding index increased from 0.28 to 0.49, indicating increasing channel segmentation and morphological instability.
5. Built-upland increased from 6,768 ha in 1990 to 20,543 ha in 2024.
6. Forest cover decreased from 12,246 ha to 8,745 ha during the same period.
7. Agricultural land declined from 54,812 ha to 49,281 ha.
8. Approximately 66.13% of the analyzed area was classified as relatively stable with respect to erosion/deposition.
9. The upper reach recorded an average migration rate of +1.38 m/year, while the lower reach showed -1.12 m/year and a dominant erosional tendency.
10. Mean annual rainfall increased from 1,702 mm during 1990-1999 to 2,146 mm during 2020-2024.
11. Built-up expansion was strongly positively correlated with net channel migration ($r = 0.71, p < 0.01$).
12. Built-up expansion was also strongly correlated with flood hazard ($r = 0.75, p < 0.01$).
13. Rainfall showed a positive relationship with mean channel width ($r = 0.64, p < 0.01$).
14. Forest and riparian vegetation conservation is important for reducing bank instability and sediment mobilisation.
15. Increasing urbanization, sand mining, infrastructure development and floodplain modification appear to be important anthropogenic controls on river instability.

Overall, the Thoubal River represents a dynamic fluvial system undergoing significant adjustment under the combined influence of monsoonal forcing, changing land cover and anthropogenic pressure. The results should be interpreted in light of the limitations associated with moderate-resolution satellite imagery, classification uncertainty, and the relative nature of the flood-hazard model. Effective management requires an integrated river-basin approach combining remote sensing, GIS, hydrological monitoring, floodplain zoning, riparian conservation, regulated sand extraction and sustainable urban development.

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