# Urbanisation and Geomorphic Transformation of the Drainage Network in the Ram Nadi Watershed, Pune, India

**Dr Shrikant M. Gabale[1] and Dr Tushar A. Shitole[2]**

**[1]Graphias Solutions Pvt. Ltd., Pune, Maharashtra, India.**

**[2]Department of Geography, Shankarrao Bhelke College, Nasarapur, Pune, Maharashtra, India.**

**DOI: https://doi.org/10.51583/IJLTEMAS.2026.150800156**

**Received: 13 September 2026; Accepted: 18 September 2026; Published: 26 September 2026**

## ABSTRACT

Urban expansion modifies watershed hydrology and geomorphology through growth of impervious cover, slope modification, channel encroachment, and disruption of low-order drainage pathways. This study evaluates land-use/land-cover (LULC) change and drainage-network transformation in the 50.95 km² Ram Nadi watershed, Pune, India. The quantitative historical analysis integrates Survey of India topographic sheets, multi-temporal Landsat imagery for 1991, 2000, 2010 and 2015, GIS-based drainage mapping, cross-profile analysis, and field reconnaissance. The legacy LULC workflow used supervised pixel-based classification in ERDAS IMAGINE; because the archived project files do not retain the classifier specification, training-sample inventory, or an independent confusion matrix, numerical accuracy statistics cannot be reconstructed and the class percentages are treated as descriptive mapped estimates. Drainage loss was assessed using an operational definition that required historical map evidence of a channel, loss or physical interruption of the mapped channel trace in 2015 spatial data, and field evidence of conversion, filling, construction, or persistent obstruction; seasonal absence of surface water alone was not considered sufficient evidence of channel loss. Settlement cover increased from 22.19% in 1991 to 47.55% in 2015, whereas agricultural land declined from 10.65% to 2.01%. Of 416 historically mapped drainage segments, 106 (25.48%) were classified as obliterated or converted by 2015, representing 47.42 km of mapped channel length; most losses occurred in first-order channels. Corrected regional calculations show that total built-up area increased from 1,165.49 ha to 2,074.81 ha, an increase of 909.32 ha (78.02%). Post-2015 institutional records from 2023-2024 indicate that wastewater discharge and channel-management pressures remain relevant within the watershed. The results demonstrate a strong spatial association between urban expansion and drainage-network fragmentation; however, event-specific flood causation cannot be established without rainfall-runoff and hydraulic modelling. The study therefore provides a geomorphic and spatial basis for drainage protection, restoration prioritisation, and future high-resolution monitoring of the Ram Nadi watershed.

**Keywords:** urbanisation; drainage-network fragmentation; land-use/land-cover change; remote sensing; GIS; low-order streams; Ram Nadi; Pune

## INTRODUCTION

Urbanisation can alter catchment response by increasing impervious and compacted surfaces, reducing infiltration, accelerating runoff production, modifying hillslope geometry, and constricting or disconnecting natural drainage corridors. Low-order streams are particularly vulnerable because they often occupy small topographic depressions that may be filled, culverted, crossed by roads, or incorporated into development plots. The hydrological consequences of these changes are well established in urban-watershed literature, although the magnitude of impact at a particular site depends on rainfall, antecedent conditions, soil and geology, drainage connectivity, and channel capacity (Leopold, 1968; Graf, 1975; Arnold & Gibbons, 1996; Booth & Jackson, 1997).

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

Ram Nadi is a tributary of the Mula River in north-western Pune and drains a rapidly urbanising peri-urban to urban landscape. The watershed includes Bhukum, Bhugaon, Bavdhan, Pashan, Baner, Aundh and adjoining localities. Earlier field observations and administrative records have documented construction pressure, wastewater inputs, debris deposition and modification of natural drainage corridors. These changes have raised concern regarding the continuity of the drainage network and the capacity of the catchment to safely convey monsoon runoff.

The earlier version of this study established a substantial spatial database but required greater methodological transparency. The present revision therefore has four objectives: (i) to quantify historical LULC change between 1991 and 2015; (ii) to define explicit criteria for identifying drainage segments that had been obliterated or physically converted; (iii) to examine the spatial relation between terrain, built-up expansion and drainage modification while avoiding unsupported causal claims; and (iv) to place the historical analysis in a more recent management context using post-2015 institutional evidence. The quantitative remote-sensing results remain a historical 1991-2015 dataset; no post-2015 LULC percentages are extrapolated without a newly validated classification.

## Study Area

The Ram Nadi watershed covers approximately 50.95 km² and lies between about 18°27'55"N and 18°33'55"N latitude and 73°42'10"E and 73°49'06"E longitude. The drainage originates in the Sahyadri uplands near Khatpewadi at approximately 955-957 m above mean sea level and descends toward the Mula River. The catchment includes the urban sectors of Aundh, Baner and Pashan, together with peri-urban settlements such as Khatpewadi, Bavdhan, Bhukum, Bhugaon, Someshwarwadi and Pirangut.

The watershed is developed largely on Deccan basalt and contains a combination of dissected uplands, hill-foot slopes, moderately sloping surfaces and lower-relief urban plains. Stream beds are commonly shallow and rocky in the less modified upper reaches. Pashan Lake and Manas Lake are major water bodies within the catchment. The juxtaposition of steep headwater terrain, developable mid-slope surfaces and dense downstream urbanisation makes the basin suitable for examining the geomorphic consequences of rapid land transformation.

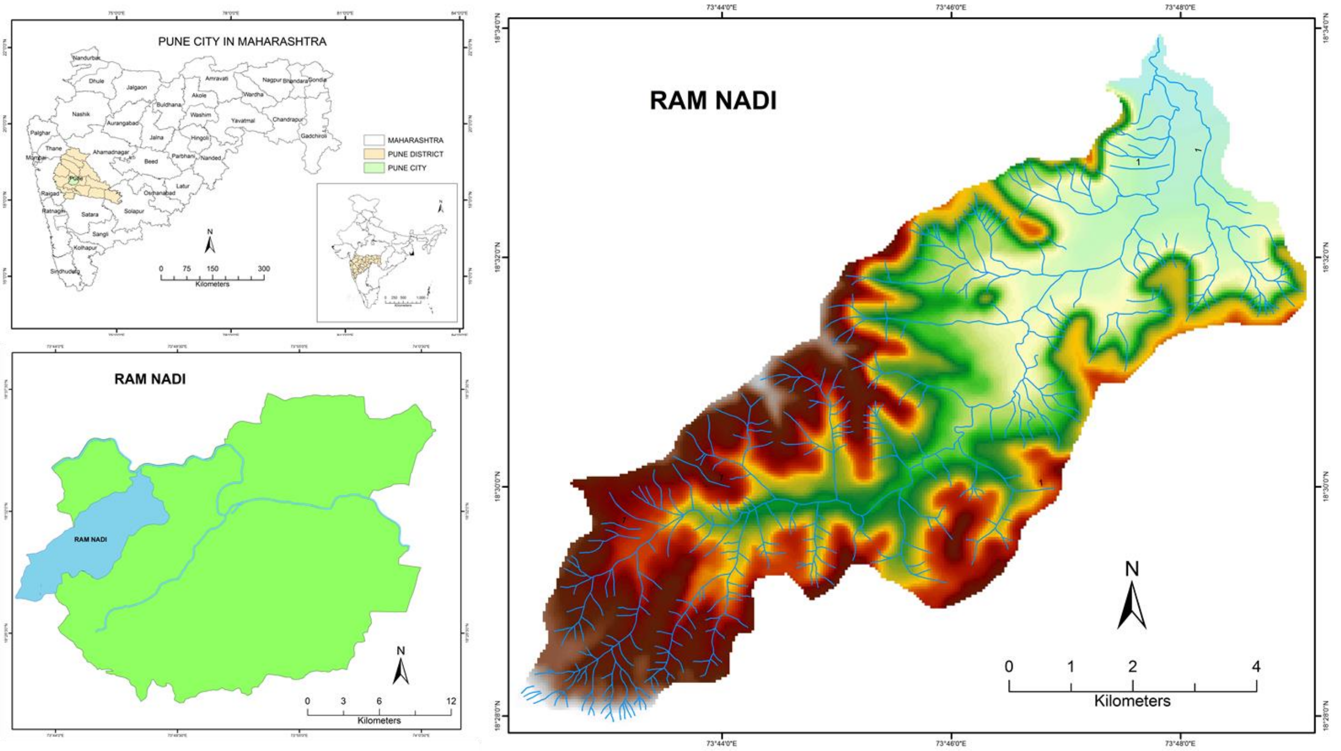


Figure 1. Location, relief and drainage setting of the Ram Nadi watershed, Pune, Maharashtra.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

# MATERIALS AND METHODS

### Study Design and Data Sources

The study combines historical spatial analysis with field-based verification. The core quantitative period is 1991-2015. Primary data consisted of reconnaissance surveys, visual observations and photographic documentation of channel condition, obstruction, construction activity, slope modification and drainage continuity. Secondary data comprised Survey of India topographic sheets, Landsat satellite imagery and relevant administrative records. Post-2015 official records were used only as contextual evidence and were not merged with the historical LULC statistics.

### Physiographic and Drainage Mapping

Contour, digital elevation model (DEM), slope, drainage and geomorphic maps were prepared from Survey of India topographic sheets 47/F/14/2, 47/F/14/3, 47/F/14/5, 47/F/14/6, 47/F/15/SE, 47/F/15/NW, 47/F/15/NE, 47/J/3/NW and 47/J/2/SW at 1:25,000 scale. The topographic base was georeferenced in a GIS environment, and the historical drainage network was digitised in ArcGIS 10.1. Stream order, stream length and watershed area were derived from the digitised network. Ten transverse profiles (R1-R10) and one longitudinal profile were used to relate valley geometry and slope to the spatial pattern of urban development.

### LULC Classification and Quality-Control Statement

Multi-temporal Landsat imagery acquired on 2 February 1991, 10 February 2000, 5 February 2010 and 12 February 2015 was used to map five LULC classes: water, vegetation, agriculture, barren/open land and settlements/built-up land. The original workflow used supervised, pixel-based classification in ERDAS IMAGINE 13, supported by visual interpretation and available field knowledge. Landsat 5 data provided 30 m multispectral information for the earlier dates; the 2015 analysis used Landsat 8 imagery. The classification outputs were compared with available field-verification checkpoints and ancillary topographic information.

The archived project record does not preserve the classifier algorithm, the number and spatial extent of class-specific training regions, or a statistically independent validation sample. Consequently, an error matrix and numerical overall, user's and producer's accuracies cannot be reconstructed retrospectively without reprocessing the original imagery. Rather than infer or invent these statistics, this study explicitly treats the historical LULC percentages as descriptive mapped estimates. Small differences between years should therefore be interpreted cautiously, particularly for classes with similar spectral responses. A future reprocessing should use a documented training design and a stratified probability-based accuracy assessment following established remote-sensing practice (Congalton, 1991; Foody, 2002; Olofsson et al., 2014).

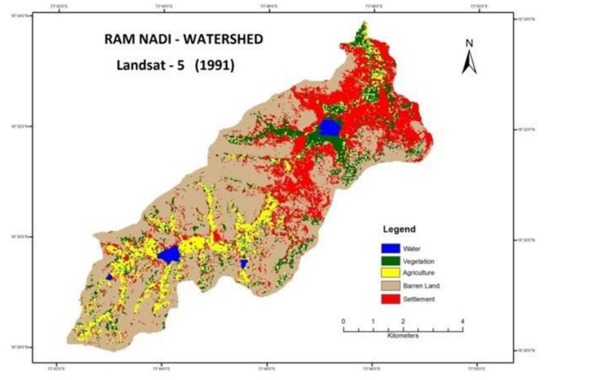


Figure 2. LULC classification of the Ram Nadi watershed, 1991.

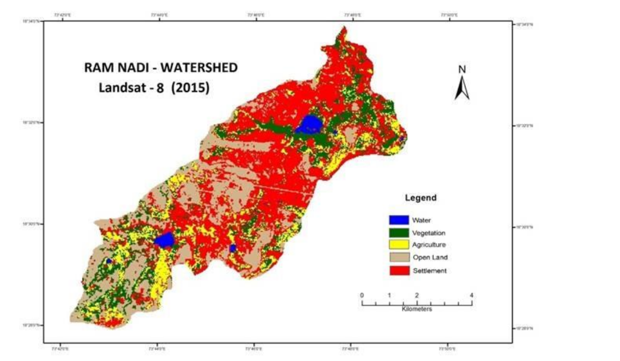


Figure 3. LULC classification of the Ram Nadi watershed, 2015.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

**Table 1. Land-use/land-cover distribution in the Ram Nadi watershed, 1991-2015 (% of mapped watershed area).**

| Class | 1991 | 2000 | 2010 | 2015 |
|---|---|---|---|---|
| Water | 1.32 | 1.26 | 1.15 | 0.91 |
| Vegetation | 10.80 | 9.43 | 8.05 | 8.22 |
| Agriculture | 10.65 | 10.45 | 8.25 | 2.01 |
| Barren/open land | 55.04 | 43.63 | 38.30 | 41.31 |
| Settlements/built-up | 22.19 | 35.43 | 44.10 | 47.55 |

Note: Values reproduce the legacy classification output; totals may differ slightly from 100% for some years because of rounding and legacy class-boundary calculations. No post-2015 LULC percentages are inferred in this study.

### Operational Definition of Obliterated/Converted Drainage Segments

The original manuscript used the term 'non-existing streams'. To reduce ambiguity, the revised paper uses the term 'obliterated or converted drainage segment'. A mapped segment was assigned to this category only where three lines of evidence converged: (1) the drainage line was present in the georeferenced historical topographic/drainage layer; (2) the corresponding channel trace was absent, interrupted, or replaced by built-up land, road/fill, or other persistent surface modification in the 2015 spatial interpretation; and (3) field reconnaissance did not identify a continuous functional channel at that location and instead recorded physical conversion, filling, construction, or persistent obstruction. Seasonal dryness or absence of visible surface water on a single satellite image was not considered sufficient evidence of stream loss. Where a dry but geomorphically identifiable channel, swale, culvert-connected flow path, or continuous valley depression remained, the segment was retained as part of the drainage network. This operational definition is designed to distinguish geomorphic loss of drainage continuity from normal seasonal variability in an intermittent monsoon catchment. Because historical field measurements are unavailable for every segment, the resulting inventory should be interpreted as a mapped estimate of drainage-network conversion rather than proof that runoff no longer follows the broader topographic flow path under extreme rainfall.

### Built-Up Area and Cross-Profile Analysis

Built-up area was quantified for profile-based regions from 1991 and 2015 classifications. For each region, absolute increase was recalculated as Built-up2015 - Built-up1991, and percentage increase as [(Built-up2015 - Built-up1991) / Built-up1991] × 100. The row-level values shown in Table 4 are computed directly from the displayed built-up areas. The regional land-area values are rounded to whole hectares, whereas the watershed total is retained from the GIS calculation; small summation differences therefore reflect rounding rather than additional mapped area.

### Recent Contextual Evidence

To improve present-day relevance without presenting unsupported post-2015 remote-sensing statistics, recent institutional records were reviewed. In Original Application No. 52/2023 before the National Green Tribunal (Western Zone Bench), a joint committee comprising representatives of the Maharashtra Pollution Control Board, Pune Municipal Corporation and Pune Metropolitan Region Development Authority undertook a site visit along the Ramnadi corridor from Bhugaon Lake to Pashan Lake on 24 July 2023 in relation to river degradation and untreated sewage concerns (National Green Tribunal, 2023). A Pune

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

Municipal Corporation drainage-department letter dated 24 April 2024, filed in the same proceedings, recorded untreated wastewater from Bhugaon and Bhukum entering Ramnadi and subsequently flowing toward Pashan Lake (Pune Municipal Corporation, 2024). These records are used as qualitative evidence that river-management pressures persisted after the historical analysis period; they do not replace a new classified satellite-image time step.

### Analytical Limitations

Three limitations are important. First, the legacy LULC classification lacks a retained independent error matrix, which limits statistical confidence in small class differences. Second, the stream-loss inventory combines historical mapping, image interpretation and field reconnaissance but does not include continuous discharge observations or high-resolution elevation change for every segment. Third, the study does not perform rainfall-runoff or hydraulic modelling; consequently, it identifies spatial associations and plausible geomorphic mechanisms but does not attribute individual flood events to a specific intervention, encroachment, retaining wall, or land-cover change. These limitations are carried explicitly into the discussion and conclusions.

## RESULTS

### LULC Change, 1991-2015

The historical classification indicates pronounced expansion of settlements/built-up land. Settlement cover increased from 22.19% in 1991 to 35.43% in 2000, 44.10% in 2010 and 47.55% in 2015, a net increase of 25.36 percentage points. Agricultural land declined from 10.65% to 2.01% (-8.64 percentage points), vegetation declined from 10.80% to 8.22% (-2.58 percentage points), and mapped water area declined from 1.32% to 0.91% (-0.41 percentage points). Barren/open land decreased markedly between 1991 and 2010 before increasing to 41.31% in 2015, indicating continuing land-surface transition and disturbance rather than a simple monotonic conversion pathway. Spatially, 1991 development was concentrated largely in the eastern and northern urban sectors around Aundh and Pashan, whereas by 2015 settlement had expanded substantially through Bavdhan and adjoining central-western sectors. The classification therefore indicates progressive westward extension of the urban footprint from the established city toward the peri-urban portion of the catchment.

### Drainage-Network Conversion

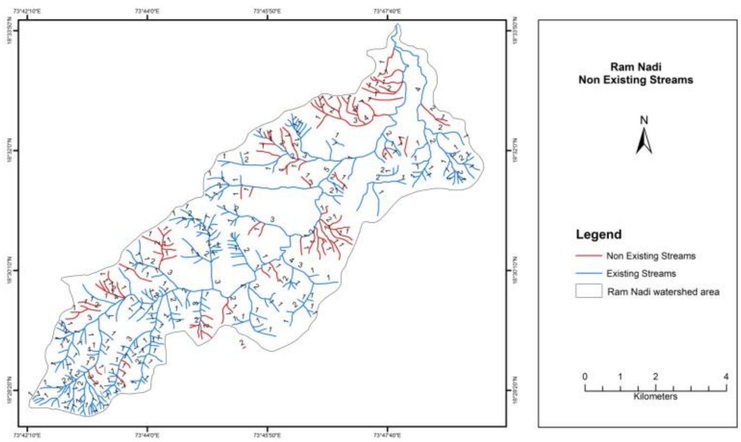


Figure 4. Historical drainage network and segments classified as obliterated/converted by 2015. The original map legend uses the term “non-existing streams”.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

The historical drainage inventory contained 416 mapped segments with a total length of 184.05 km. By 2015, 106 segments (25.48%) with a mapped length of 47.42 km met the operational criteria for obliteration or physical conversion. Loss was concentrated in first-order drainage: 86 of 323 first-order segments were classified as obliterated, accounting for 37.30 km of mapped length. Sixteen second-order, three third-order and one fourth-order segments were also affected; the single fifth-order channel remained mapped.

**Table 2. Stream-order-wise inventory of historical drainage and segments classified as obliterated/converted by 2015.**

| Stream order | Historical no. of segments | Historical length (km) | Obliterated/converted by 2015 | Affected length (km) | Share of order affected (%) |
|---|---|---|---|---|---|
| 1st | 323 | 109.14 | 86 | 37.30 | 26.63 |
| 2nd | 67 | 30.75 | 16 | 8.24 | 23.88 |
| 3rd | 21 | 22.62 | 3 | 1.08 | 14.29 |
| 4th | 4 | 11.65 | 1 | 0.80 | 25.00 |
| 5th | 1 | 9.89 | 0 | 0.00 | 0.00 |
| **Total** | **416** | **184.05** | **106** | **47.42** | **25.48** |

The concentration of mapped loss in first-order channels is geomorphically significant because these small headwater and hillslope drainage elements provide connectivity between local runoff-generating areas and the higher-order network. Their conversion does not necessarily eliminate all stormflow along the former alignment; instead, it can redirect or concentrate runoff through roads, plot boundaries, storm drains and residual depressions.

**Field Observations and Spatial Pattern of Modification**

Field reconnaissance identified repeated examples of channel narrowing, debris deposition, construction across or adjacent to mapped drainage paths, and slope cutting in the Bhukum-Bhugaon-Bavdhan-Pashan corridor. The mapped pattern is consistent with more intensive transformation in the middle and lower watershed, where urban expansion has been greatest. In the Chandani Chowk-Bavdhan sector, the historical drainage layer indicates loss or interruption of several low-order tributaries in areas now occupied by roads and urban development.

These observations support an association between urban growth and drainage-network fragmentation but do not, by themselves, establish the hydrological contribution of any single obstruction to a particular flood. Likewise, the presence of retaining structures along channel margins may alter local cross-sectional geometry where they encroach into the active conveyance zone, but the direction and magnitude of hydraulic effects require surveyed cross-sections, design details and hydraulic modelling. The revised interpretation therefore avoids attributing observed flooding to retaining walls or encroachment without site-specific hydraulic evidence.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

## Cross-Profile and Slope-Gradient Relationships

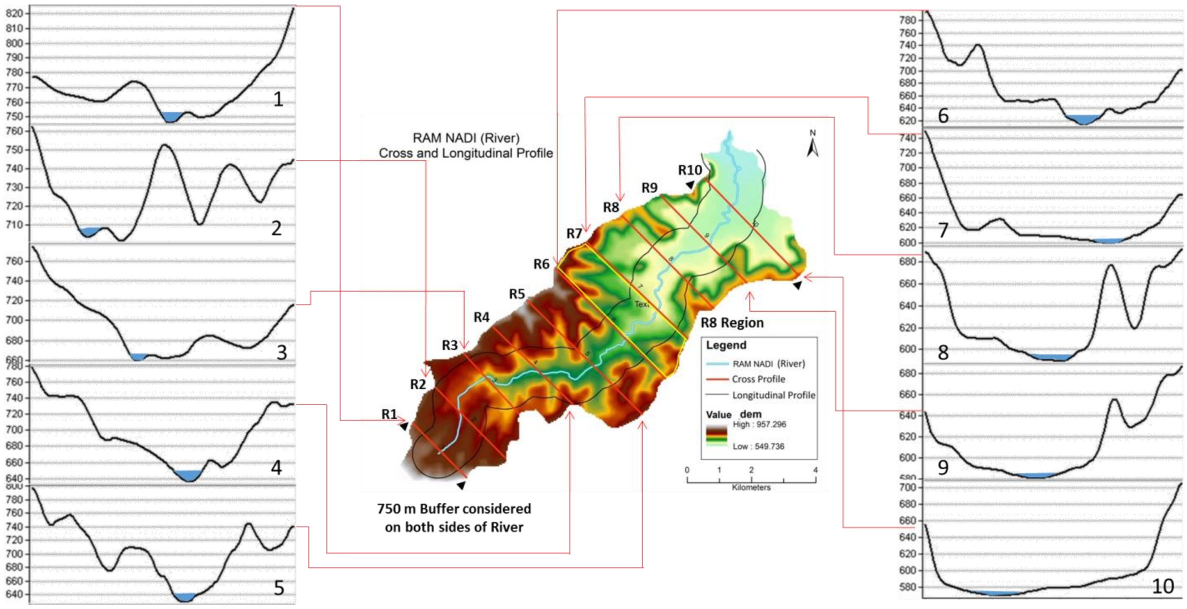


Figure 5. Transverse profiles R1-R10 and longitudinal profile used to relate valley geometry, slope and settlement expansion.

**Table 3. Latitudinal slope, gradient and relative-height characteristics along the Ram Nadi cross profiles.**

| Profile | West A (m) | Rel. ht. A-R (m) | Gradient | Slope (°) | Slope (%) | River (m) | Rel. ht. B-R (m) | Gradient | Slope (°) | Slope (%) | East B (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R1 | 762 | 16 | 1:47 | 1.22 | 2 | 746 | 29 | 1:26 | 2.21 | 4 | 775 |
| R2 | 761 | 59 | 1:13 | 4.50 | 8 | 702 | 17 | 1:44 | 1.30 | 2 | 719 |
| R3 | 736 | 76 | 1:10 | 5.79 | 10 | 660 | 25 | 1:30 | 1.91 | 3 | 685 |
| R4 | 688 | 51 | 1:15 | 3.89 | 7 | 637 | 94 | 1:8 | 7.14 | 13 | 731 |
| R5 | 707 | 78 | 1:10 | 5.94 | 10 | 629 | 59 | 1:13 | 4.50 | 8 | 688 |
| R6 | 764 | 148 | 1:5 | 11.16 | 20 | 616 | 22 | 1:34 | 1.68 | 3 | 638 |
| R7 | 609 | 9 | 1:83 | 0.69 | 1 | 600 | 23 | 1:33 | 1.76 | 3 | 623 |
| R8 | 601 | 11 | 1:68 | 0.84 | 1 | 590 | 87 | 1:9 | 6.62 | 12 | 677 |
| R9 | 610 | 21 | 1:36 | 1.60 | 3 | 589 | 44 | 1:17 | 3.36 | 6 | 633 |
| R10 | 594 | 24 | 1:31 | 1.83 | 3 | 570 | 7 | 1:107 | 0.53 | 1 | 577 |

The R5-R7 sector contains slopes that are locally suitable for construction and has experienced substantial development. The profile analysis shows that urban growth has not occurred uniformly across the basin: steeper or institutionally constrained areas remain less developed, whereas moderate-slope sectors close to existing transport and service corridors have urbanised more rapidly. The profile results are therefore

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

interpreted as a topographic control on development opportunity, not as direct evidence that slope alone determines flood response.

**Corrected Built-Up Area Analysis**

**Table 4. Corrected built-up area analysis by profile region, 1991-2015.**

| Profile/region | Region area (ha) | Built-up 1991 (ha) | Built-up 2015 (ha) | Increase (ha) | Increase (%) |
|---|---|---|---|---|---|
| > R1 | 204 | 8.29 | 10.00 | 1.71 | 20.63 |
| R1-R2 | 346 | 12.95 | 16.00 | 3.05 | 23.55 |
| R2-R3 | 405 | 4.14 | 22.00 | 17.86 | 431.40 |
| R3-R4 | 398 | 56.98 | 60.00 | 3.02 | 5.30 |
| R4-R5 | 591 | 46.62 | 124.00 | 77.38 | 165.98 |
| R5-R6 | 598 | 47.14 | 106.00 | 58.86 | 124.86 |
| R6-R7 | 604 | 152.81 | 272.00 | 119.19 | 78.00 |
| R7-R8 | 511 | 178.71 | 246.00 | 67.29 | 37.65 |
| R8-R9 | 481 | 147.63 | 285.00 | 137.37 | 93.05 |
| R9-R10 | 498 | 253.82 | 487.00 | 233.18 | 91.87 |
| R10-next | 460 | 256.41 | 447.00 | 190.59 | 74.33 |
| **GIS total** | **5095.20** | **1165.49** | **2074.81** | **909.32** | **78.02** |

Note: Regional area values are displayed as rounded whole hectares, while the GIS total retains decimals; therefore, the sum of displayed regional areas differs slightly from the exact watershed total. Row-level increases and percentages have been recalculated directly from the displayed 1991 and 2015 values. The total built-up increase is based on the GIS totals: 2,074.81 - 1,165.49 = 909.32 ha (78.02%).

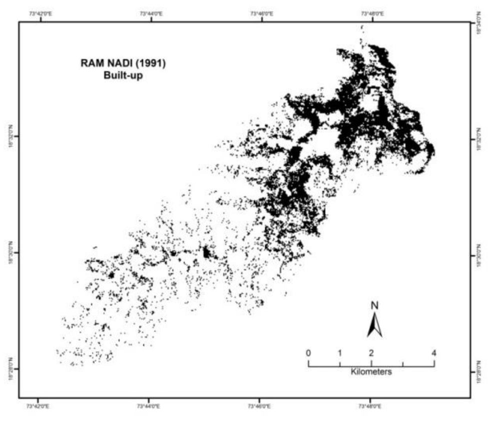


Figure 6. Built-up distribution, 1991.

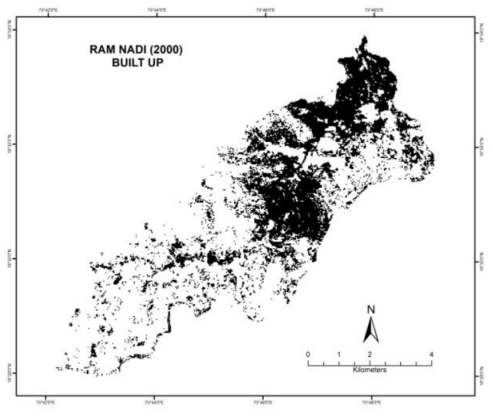


Figure 7. Built-up distribution, 2000.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

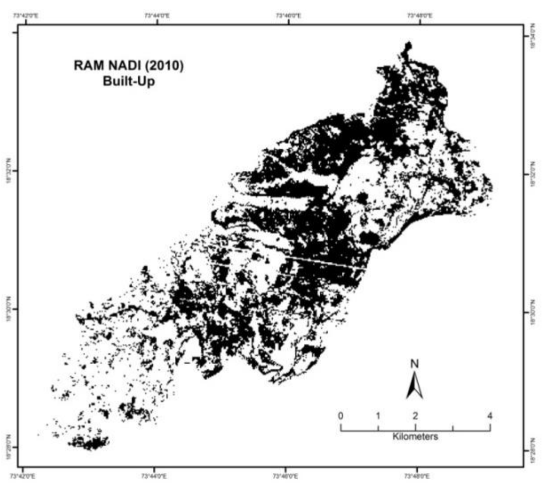


Figure 8. Built-up distribution, 2010.

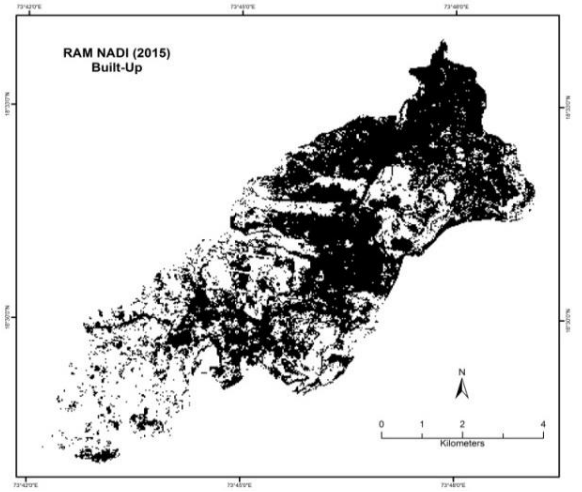


Figure 9. Built-up distribution, 2015.

The corrected calculations show that mapped built-up area increased from 1,165.49 ha in 1991 to 2,074.81 ha in 2015, a net increase of 909.32 ha (78.02%). The largest proportional change occurred in R2-R3 because of its low 1991 base, whereas the largest absolute increases occurred in R9-R10 (233.18 ha), R10-next (190.59 ha), R8-R9 (137.37 ha) and R6-R7 (119.19 ha). This pattern confirms that the magnitude of change should be evaluated using both absolute and percentage measures.

**Post-2015 Context**

The 2023 NGT joint-committee site inspection and the 2024 PMC drainage correspondence show that wastewater discharge and river-management concerns continued after the 2015 endpoint of the satellite analysis. These recent records are consistent with the broader interpretation that the Ram Nadi corridor remains under urban and infrastructure pressure. They do not, however, quantify post-2015 built-up expansion or drainage loss. The present paper therefore separates the validated historical comparison from recent qualitative evidence rather than extending the 1991-2015 trend line beyond the available classification.

## DISCUSSION

**Urban Expansion and Drainage Fragmentation**

The principal finding is the spatial concurrence of rapid built-up growth and widespread modification of low-order drainage elements. The settlement class more than doubled as a share of mapped watershed area between 1991 and 2015, while approximately one quarter of historically mapped drainage segments met the operational criteria for obliteration or physical conversion. The dominance of first-order segments among the affected channels is consistent with the greater exposure of small headwater and hillslope flow paths to plot development, filling, road construction and local grading.

The results should not be interpreted as evidence that every mapped stream loss is caused by a single type of urban intervention. Multiple processes may contribute, including grading, culverting, debris accumulation, construction over shallow drainage depressions, road embankments and subsequent storm-drain routing. Similarly, the hydrological consequence of a converted segment depends on whether flow is blocked, redirected, piped or concentrated elsewhere.

**Implications for Flooding and Channel Management**

Urbanisation can increase runoff volumes and peak rates by expanding impervious cover and reducing infiltration, while drainage constriction can reduce local conveyance. The observed spatial pattern therefore

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

provides a physically plausible basis for increased drainage stress during intense monsoon rainfall. However, the present dataset does not include event-based rainfall, discharge, surveyed hydraulic cross-sections or modelled water levels. Statements regarding flash-flood causation are therefore framed as hypotheses supported by spatial association and field evidence rather than as demonstrated causal attribution.

The same caution applies to retaining walls and bank protection. Such structures may improve bank stability or, if they project into the active channel, reduce effective conveyance. Their net effect is site-specific and should be evaluated through surveyed cross-sections and hydraulic modelling. This revised interpretation replaces earlier categorical statements regarding flood impacts of retaining walls with an evidence-based requirement for hydraulic assessment.

**Management Significance and Future Monitoring**

The drainage inventory provides a useful basis for prioritising protection of remaining first- and second-order channels, verifying historical alignments before development approval, and identifying locations where channel continuity should be restored or maintained. A current drainage audit should use sub-metre or very-high-resolution imagery, UAV-derived terrain where permissible, and field verification to distinguish open channels, culverts, filled depressions and engineered storm-drain connections.

A full update of the historical analysis should add a recent Sentinel-2 or Landsat 8/9 time step and apply a reproducible classifier with documented training samples and independent validation. Because urban classes and dry barren surfaces can be spectrally similar, the updated workflow should report a confusion matrix, overall accuracy, class-wise user's and producer's accuracies, and area-adjusted estimates where appropriate. Coupling the revised LULC and drainage layers with rainfall-runoff and two-dimensional hydraulic modelling would allow the geomorphic evidence presented here to be translated into quantitative flood-risk scenarios.

## CONCLUSION

The Ram Nadi watershed underwent major land transformation between 1991 and 2015. Mapped settlement cover increased from 22.19% to 47.55%, while agricultural land declined from 10.65% to 2.01%. The historical drainage inventory comprised 416 mapped segments; 106 segments (25.48%), representing 47.42 km of channel length, were classified as obliterated or physically converted by 2015 under an explicit three-part criterion combining historical mapping, 2015 spatial interpretation and field evidence. First-order channels accounted for most of the mapped loss.

Recalculation of the regional built-up statistics resolves inconsistencies in the earlier table and indicates a total increase of 909.32 ha (78.02%) between 1991 and 2015. Cross-profile analysis shows that growth was concentrated in specific middle and downstream sectors rather than uniformly across the basin. Recent official records from 2023-2024 further indicate that wastewater and river-management pressures remain relevant, although they are not used to extrapolate post-2015 LULC change.

The evidence supports a strong spatial association between urban expansion, geomorphic modification and drainage-network fragmentation. It does not, however, establish the contribution of individual structures or land-cover changes to particular flood events. Future work should therefore combine updated, accuracy-assessed satellite classification with high-resolution drainage mapping, field surveys and hydrological-hydraulic modelling. Such an integrated approach would provide a defensible basis for protecting remaining drainage corridors, restoring disrupted connectivity and managing flood risk in the rapidly urbanising Ram Nadi watershed.

**Data and Reproducibility Statement**

The historical maps, Landsat-derived classifications, topographic sheets and field observations used in the original study form the basis of the present analysis. The archived classification project does not retain complete training-sample metadata or an independent validation matrix; these limitations are stated explicitly and no accuracy statistics have been retrospectively invented. The corrected calculations in Table 4 are fully reproducible from the displayed 1991 and 2015 built-up values. A future updated analysis should archive the classifier parameters, training polygons, validation sample and accuracy matrix together with the resulting GIS layers.

## REFERENCES

1. Arnold, C. L., & Gibbons, C. J. (1996). Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association, 62(2), 243-258.
2. Bhailume, S. A. (2011). A geographical study of civic amenities in PMC area using GIS techniques. International Journal of India Streams Research Journal, 4, 188-192.
3. Bhaskar, P. (2012). Urbanization and changing green spaces in Indian cities (case study - city of Pune). International Journal of Geology, Earth and Environmental Sciences, 2(2), 148-156.
4. Bloom, A. L. (2002). Geomorphology - A systematic analysis of late Cenozoic landforms (3rd ed.). New Delhi, India: Prentice-Hall of India Private Limited, pp. 419-458.
5. Booth, D. B., & Jackson, C. R. (1997). Urbanization of aquatic systems - Degradation thresholds, stormwater detention, and the limits of mitigation. Journal of the American Water Resources Association, 22(5).
6. Brunsden, D. (1970). Slopes form and process. Institute of British Geographers Special Publication, London.
7. Census of India. (2011). House listing and housing census schedule. Government of India.
8. Chengtai, D. (1995). An approach to theory and methods of urban geomorphology. Chinese Geographical Science, 6, 88-95.
9. City Development Plan Report. (2012). Pune Municipal Corporation, Maharashtra, India. Indo-USAID Financial Institutions Reform and Expansion Project - Debt and Infrastructure Component (FIRE-D Project).
10. Coates, D. (1976). Urban geomorphology. Geological Society of America, Boulder, CO, USA.
11. Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment, 37(1), 35-46.
12. Cooke, R. U., & Doornkamp, J. C. (1974). Geomorphology in environmental management (pp. 8-20). Ely House, London: Oxford University Press. ISBN 0198740212.
13. Cooke, R. U., Brunsden, D., Doornkamp, J., & Jones, D. (1982). Urban geomorphology in drylands (pp. 72-106). New York: Oxford University Press.
14. Dikshit, K. R. (1986). Maharashtra in maps. Bombay: Maharashtra State Board for Literature and Culture.
15. Dingman, S. L. (2009). Fluvial hydraulics (pp. 20-94). New York: Oxford University Press.
16. Dixit, K., & Ahmed, I. (1998). Managing the Himalayan watershed - A flood of questions. Economic and Political Weekly, 33(44).
17. Duraiswami, R. A., Dumale, V., & Shetty, U. (2009). Geospatial mapping of potential recharge zones in parts of Pune city. Journal of the Geological Society of India, 73, 621-638.
18. Easterbrook, D. J. (1969). Principles of geomorphology. New York: McGraw-Hill Book Company.
19. Environmental Status Report. (2012-13). Pune Municipal Corporation and The Energy and Resources Institute (TERI).
20. Foody, G. M. (2002). Status of land cover classification accuracy assessment. Remote Sensing of Environment, 80(1), 185-201.
21. Fracassi, C. P., & de Lollo, J. A. (2013). Urban sprawl in small cities: Analysis of the municipality of São Pedro (SP) - potentials and constraints. Journal of Urban and Environmental Engineering, 7(1), 64-73.
22. Geological Survey of India. (1996). Contribution in environmental geology (Special Publication No. 43, pp. 1-265). New Delhi, Government of India.
23. Goudie, A. S. (2004). Encyclopaedia of geomorphology. London: Routledge.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026

24. Government of India. (2004). Guidelines for conservation, development and management of urban greens. Ministry of Environment, Forests & Climate Change, Forest Policy Division, F. No. 1-2/2004-FP.
25. Graf, W. L. (1975). The impact of suburbanization on fluvial geomorphology. Water Resources Research, 11(5), 690-692.
26. Gregory, K. J., & Park, C. (1974). Adjustment of river channel capacity downstream from a reservoir. Water Resources Research, 10(4), 870-873.
27. Hack, J. T., & Goodlett, J. C. (1960). Geomorphology and forest ecology of a mountain region in the central Appalachians (U.S. Geological Survey Professional Paper 347, p. 66).
28. Hammer, Ø., Harper, D. A. T., & Ryan, P. D. (2001). PAST: Paleontological statistics software package for education and data analysis. Palaeontologia Electronica, 4(1), 9pp.
29. Joglekar, P. P., Deo, S. G., Balakawade, P., Deshpande-Mukherjee, A., Rajaguru, S. N., & Kulkarni, A. N. (2006-07). A new look at ancient Pune through salvage archaeology. Bulletin of the Deccan College Post-Graduate and Research Institute, 66-67, 211-225.
30. Kale, V. S., & Gupta, A. (2001). Introduction to geomorphology (pp. 82-101). India: Orient Longman Ltd.
31. Kumar, A., & Pandey, R. N. (1981). Morphometric analysis of some drainage basins of the Hazaribagh Plateau region. The National Geographical Journal of India, 27(1-2), 50-59.
32. Leopold, L. B. (1968). Hydrology for urban land planning - A guidebook on the hydrological effects of urban land use (U.S. Geological Survey Circular 554).
33. McDonnell, M. J., & Pickett, S. T. A. (1990). Ecosystem structure and function along urban-rural gradients: An unexploited opportunity for ecology. Ecology, 71, 1232-1237.
34. National Atlas and Thematic Mapping Organisation. (1996). Geomorphological mapping, perspective and dimensions (Monograph 13; P. Nag & G. N. Saha, Eds.). Calcutta, Government of India.
35. National Environmental Engineering Research Institute. (2011). Report on the current status of the Mithi River and possible solutions.
36. National Green Tribunal. (2023). Joint Committee Report in Original Application No. 52/2023, Krunnal Narayan Gharre v. Pune Municipal Corporation & Ors.; site inspection of the Ramnadi corridor on 24 July 2023.
37. Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E., & Wulder, M. A. (2014). Good practices for estimating area and assessing accuracy of land change. Remote Sensing of Environment, 148, 42-57.
38. Pareta, K., & Pareta, U. (2011). Quantitative morphometric analysis of a watershed of Yamuna basin, India, using ASTER (DEM) data and GIS. International Journal of Geomatics and Geosciences, 2(1), 248-269.
39. Pune Municipal Corporation. (2014). Water Supply Department: Presentation on water supply in Pune city.
40. Pune Municipal Corporation. (2024). Sewage Maintenance & Repairing Department Letter O. No. 169, dated 24 April 2024, concerning untreated wastewater from Bhugaon and Bhukum entering Ramnadi; filed in Original Application No. 52/2023 before the National Green Tribunal, Western Zone Bench, Pune.
41. Punithavathi, J., Tamilenthi, S., & Baskaran, R. (2011). Geomorphological interpretation and urban sprawl details of Thanjavur district, Tamil Nadu. World Journal of Science and Technology, 1(4), 19-27.
42. Sawant, S. B. (1978). The city of Poona: A study in urban geography (pp. 15-29). University of Pune, Pune.
43. Shekhar, S. (2012). Detecting slums from QuickBird data in Pune using an object-oriented approach. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIX-B8, 519-524.
44. Singh, H. S. (2012). Status of tree cover in urban areas of Gujarat, trees in municipal corporations and municipalities: Tree counting in urban and sub-urban areas - 2011. Gujarat Forest Department.
45. Strahler, A. N. (2011). Physical geography (4th ed., p. 455). Singapore: John Wiley and Sons.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue VIII September 2026


46. Thornbury, W. D. (1954). Principles of geomorphology (2nd ed.). University of California. ISBN 978-8123908113.
47. United Nations General Assembly. (1987). Report of the World Commission on Environment and Development: Our common future.
48. United States Geological Survey. (2015). Landsat 8 data products. http://landsat.usgs.gov
49. World Commission on Environment and Development. (1987). Our common future. Oxford: Oxford University Press. ISBN 019282080X.
50. Zipperer, W. C., Sisinni, S. M., & Pouyat, R. V. (1997). Urban tree cover: An ecological perspective. Urban Ecosystems, 1, 229-246.