

Spatial Assessment of Urbanization and Groundwater Stress in Velachery, Chennai: A Comparative Analysis of LULC and Groundwater Levels

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ABSTRACT

Rapid urban expansion in coastal Indian cities is associated with changes in land cover and may place pressure on water resources. This study compares land use/land cover (LULC) and groundwater depth in Velachery, Chennai, for 2017 and 2024. Esri 10 m Sentinel-2 based LULC layers were quantified in ArcGIS Pro from pixel counts, and class-wise change was summarised in a change detection matrix. Groundwater depth data from the Central Ground Water Board (CGWB) were interpolated using the inverse distance weighted (IDW) method. The area was already about 90% built-up in 2017. Built-up area increased from 1,774.13 ha to 1,796.91 ha (+1.28%), while water bodies decreased from 50.02 ha to 41.13 ha (-17.77%), tree cover from 93.73 ha to 80.62 ha (-13.99%) and rangeland from 34.64 ha to 29.11 ha (-15.96%). At the Velachery observation point, depth to groundwater changed from 8.118 m in 2017 to 4.010 m in 2024 (-4.108 m), and the interpolated depth range narrowed from 3.294–8.160 m to 3.250–4.406 m. The continued loss of water bodies and vegetation in an already densely built-up area may have contributed to a reduced capacity for natural recharge, and the results suggest a potential relationship between urban growth and pressure on water resources. The shallower groundwater depth in 2024 may be associated with rainfall and seasonal conditions and should not be read alone as a sign of reduced urban pressure. The findings support recharge-oriented planning, protection of the remaining water bodies and continued groundwater monitoring.

INTRODUCTION

Urbanization is one of the most visible forms of land use change of the present century. More than half of the world's population now lives in urban areas, and this share is projected to keep rising, with much of the growth expected in Asia and Africa (United Nations, 2019). Conversion of natural and agricultural land into built-up surfaces is associated with changes in how water is stored, moved and used within a landscape, and land use change is recognised as a major driver of alterations in the hydrological cycle (Foley et al., 2005).

In cities, roads, roofs and paved surfaces replace soil and vegetation. Reviews of watershed hydrology indicate that increasing impervious cover is associated with reduced infiltration, higher surface runoff and faster delivery of water to drains and streams (Shuster et al., 2005). The ecological and hydrological degradation that accompanies this has been described as the “urban stream syndrome” (Walsh et al., 2005). The relationship with groundwater is less direct and more variable. Land use and land cover change may either reduce or increase recharge depending on climate, soil and the type of change (Scanlon et al., 2005). In cities, recharge may also be influenced by leakage from water supply and sewer networks, which in some cases can exceed natural recharge from rainfall (Lerner, 1990; Wakode et al., 2018). Studies from Hyderabad suggest that urban expansion and densification are associated with changes in both groundwater levels and groundwater quality, with falling levels in areas of heavy abstraction and rising levels where sewage and effluents recharge the aquifer (Wakode et al., 2014).



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Chennai, a large metropolitan city on the Coromandel Coast, has expanded rapidly over the last few decades. Studies of south Chennai have linked urban growth with changes in groundwater conditions (Arunprakash et al., 2014). A remote sensing and GIS analysis of Chennai for 2005–2016 reported an increase of 15.36% in compact built-up area and a decrease of 5.24% in water bodies (MuraliKrishna & Sahithi, 2023), and recent modelling work suggests that future LULC change in Chennai may influence groundwater recharge (Sadath et al., 2024). Velachery, in the south of the city, is a densely built residential and commercial locality that lies close to low-lying wetland areas, which makes the relationship between land cover and water resources particularly relevant.

Remote sensing and geographic information systems (GIS) offer consistent and repeatable ways to study such changes. The Sentinel-2 mission provides multispectral imagery at 10 m resolution for land monitoring (Drusch et al., 2012), and annual global LULC maps have been produced from it using deep learning (Karra et al., 2021). Change detection techniques allow class-wise comparison of LULC between dates (Lu et al., 2004), and interpolation methods such as

inverse distance weighting (Shepard, 1968) convert point measurements of groundwater depth into continuous surfaces. However, few studies place a fine-scale LULC comparison beside groundwater depth mapping for a small urban locality such as Velachery. This paper addresses that gap by comparing LULC and groundwater depth for 2017 and 2024.

STUDY AREA

Velachery is a locality in south Chennai, the capital of Tamil Nadu, on the Coromandel Coast of the Bay of Bengal (Figure 1). The study boundary used in this work covers about 1,965 ha (approximately 19.65 km²), estimated from the LULC pixel totals, and lies roughly between latitudes 12°58' N and 13°01' N and longitudes 80°12' E and 80°17' E. On the base map (Figure 1) the boundary is bordered by the Adyar River and the Guindy area on the north, by the Bay of Bengal on the east, and by the coastal neighbourhoods of Kottivakkam, Palavakkam and Neelankarai to the south-east. The campus of the Indian Institute of Technology Madras lies within the notch of the boundary on its northern side, and a low-lying tract with water bodies lies to the south and south-west of the boundary.

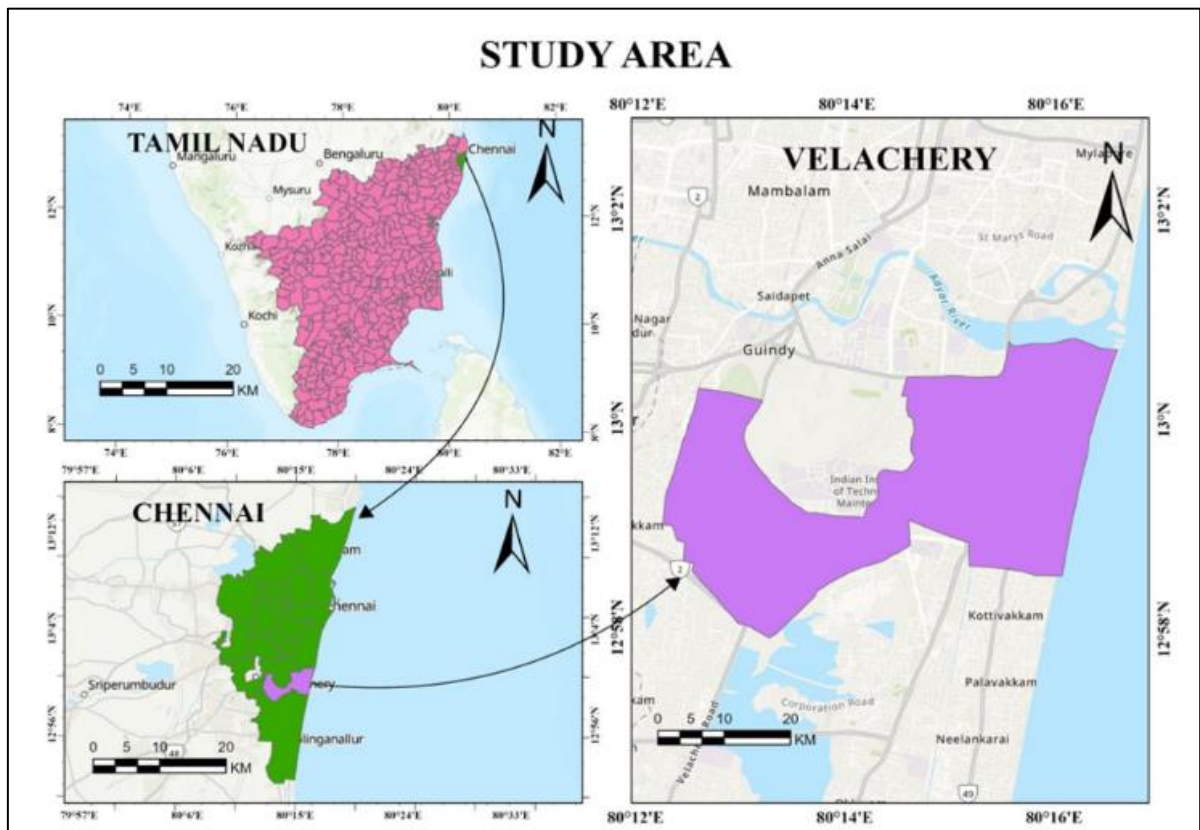


Fig.1: Location of the study area: Tamil Nadu, Chennai and the Velachery study boundary.

Chennai has a tropical, hot and humid climate. Rainfall is received mainly from the north-east monsoon between October and December, and the average annual rainfall is of the order of 1,200 mm. The terrain is low-lying and flat with a very gentle slope towards the sea, so intense monsoon rainfall and cyclonic storms can cause widespread flooding, and Velachery was among the localities severely affected during the December 2015 floods. The area is drained by the Adyar River system and by a network of lakes, tanks and marshes that have historically acted as detention and recharge features. The coastal plain of Chennai underlain

by recent alluvium and sandy and clayey sediments over older sedimentary and crystalline rocks, and shallow unconfined groundwater occurs in the alluvial and sandy layers. Because the study area is close to the coast, groundwater may also be exposed to seawater influence where abstraction increases. Over the past two decades Velachery has developed into a major residential, commercial and information technology zone with dense housing and heavy traffic. This is reflected in the LULC maps of this study, in which about 90% of the area is already built-up in 2017. The salient features of the study area are summarised in Table 1.

Table 1. Salient features of the study area.

Feature	Description
Location	Velachery, south Chennai, Tamil Nadu, India
Approximate extent	12°58'–13°01' N; 80°12'–80°17' E
Area	About 1,965 ha (19.65 km ²), from the LULC pixel totals
Physical setting	Low-lying, gently sloping coastal plain; Adyar River to the north and Bay of Bengal to the east
Climate	Tropical, hot and humid; rainfall mainly from the north-east monsoon (October–December)
Aquifer setting	Shallow unconfined groundwater in alluvial and sandy sediments of the coastal plain
Land use character	Dense residential, commercial, institutional and IT development; about 90% built-up in 2017
Key water features	Adyar River, lakes and tanks, low-lying marshy tract to the south, and the Bay of Bengal coast

MATERIALS AND METHODS

Two types of data were used: land use and land cover for 2017 and 2024 derived from Sentinel-2 satellite data, and groundwater depth data for the same two years. All spatial processing was carried out in ArcGIS Pro (Table 2).

Table 2. Data and software used in the study.

Data/software	Source and description	Purpose
LULC data (2017 and 2024)	Esri 10 m land cover derived from Sentinel-2 satellite data (Karra et al., 2021)	LULC mapping, area statistics and change detection
Groundwater level data	Central Ground Water Board (CGWB) groundwater depth data (m)	Groundwater depth mapping and change analysis
GIS software	ArcGIS Pro	Pixel counts, IDW interpolation, map layout

Three techniques were applied: (i) LULC classification and quantification for the seven classes present in the study area (water, trees, flooded vegetation, crops, built area, bare ground and range land); (ii) IDW interpolation for groundwater depth mapping; and (iii) spatial analysis, including class-wise change detection and point-based depth comparison.

Satellite-derived LULC data (2017 and 2024) and groundwater depth data were collected. The imagery was pre-processed and enhanced for analysis. Land use and land cover was classified for both years, and the pixel count of each class was obtained. Class-wise area for 2017 was compared with that for 2024, and the net change and percentage change were tabulated. The groundwater depth data were prepared and validated before interpolation. Groundwater depth maps for 2017 and 2024 were prepared by IDW interpolation and divided into depth classes. LULC change and groundwater depth change were compared to examine the potential relationship between urbanization and water resources.

LULC area calculation

The LULC data have a spatial resolution of 10 m, so each pixel represents 100 m². The area and percentage of each class were

calculated from the pixel count as follows:

$$\text{Area of one pixel} = 10 \text{ m} \times 10 \text{ m} = 100 \text{ m}^2$$

$$\text{Area (hectares)} = \text{Count} \times 100 / 10,000$$

$$\text{LULC percentage} = (\text{Class area} / \text{Total LULC area}) \times 100$$

Groundwater depth mapping and change analysis

Groundwater depth at unsampled locations was estimated by IDW interpolation, in which the value at a location is a distance-weighted average of the surrounding observations:

$$Z(x_0) = \sum (w_i \cdot Z_i) / \sum w_i, \text{ with } w_i = 1 / d_i^p$$

where $Z(x_0)$ is the estimated depth, Z_i is the observed depth at point i , d_i is the distance from point i to the location being estimated and p is the power parameter (Shepard, 1968). The resulting surfaces were divided into depth classes for 2017 and 2024 (pre-monsoon). The change in depth at the observation point was calculated as:

$$\text{Change} = 2024 \text{ depth} - 2017 \text{ depth}$$

A negative value indicates that the water level was closer to the ground surface in 2024 than in 2017, and a positive value indicates that it was deeper.

RESULTS AND DISCUSSION

Land use and land cover in 2017

The LULC map of 2017 (Figure 2) shows that the study area is predominantly built-up. Built area covered 1,774 ha, which is about 90% of the mapped area (Table 3). Trees formed the second largest class with 93 ha (5%) and are concentrated in the north-eastern part of the study area near the Adyar estuary. Water bodies covered 50 ha (3%) and occur as small isolated patches, mainly in the west and centre.

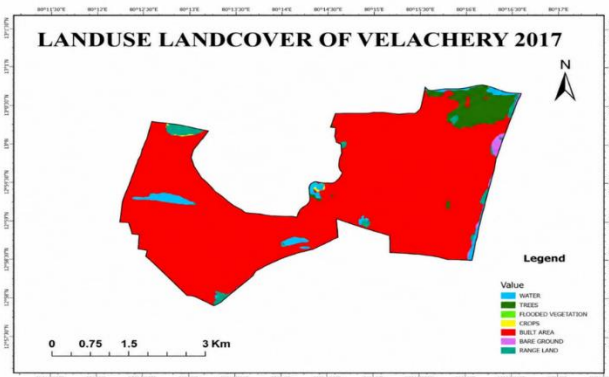


Fig. 2: Land use and land cover map of Velachery, 2017.

Range land (35 ha; 2%), bare ground (10 ha; 1%), crops (2 ha) and flooded vegetation (0.3 ha) together account for a very small share of the area. Eastern coastal belt near

Sholinganallur and Mahabalipuram, suggesting relatively lower ionic concentrations and minimal anthropogenic influence in these localities.

The LULC calculation was based on the 10 m resolution of the data, using Area of 1 pixel = $10 \times 10 = 100 \text{ m}^2$, Area (hectares) = $\text{Count} \times 100 / 10,000$ and LULC percentage = $(\text{Class area} / \text{Total LULC area}) \times 100$.

Table 3. LULC statistics of Velachery, 2017.

S.NO	FEATURES	COUNT	AREA	PERCENTAGE
1	Water	5002 $\times 100/10,000$	50	3%
2	Trees	9373 $\times 100/10,000$	93	5%
3	Flooded vegetation	39 $\times 100/10,000$	0.3	0%
4	Crops	196 $\times 100/10,000$	2	0%
5	Built Area	177413 $\times 100/10,000$	1774	90%
6	Bare ground	1030 $\times 100/10,000$	10	1%
7	Range land	3464 $\times 100/10,000$	35	2%

Land use and land cover in 2024

By 2024 the built area had increased to 1,797 ha (91%) (Figure 3 and Table 4). Water bodies decreased to 41 ha (2%), tree cover to 80 ha (4%) and range land to 29 ha (1%).

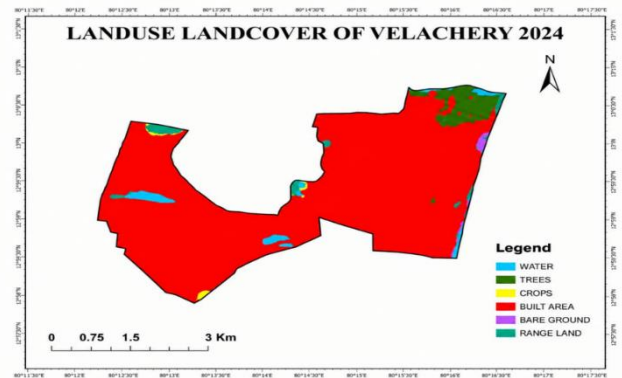


Fig.3: Land use and land cover map of Velachery, 2024.

Flooded vegetation, which was a very small class in 2017, is not present in the 2024 classification. Crops increased to 7.6 ha, which is still a very small share of the area.

Table 4. LULC statistics of Velachery, 2024.

S.NO	FEATURES	COUNT	AREA	PERCENTAGE
1	Water	4114×100/10,000	41	2%
2	Trees	8077×100/10,000	80	4%
3	Crops	756×100/10,000	7.6	0%
4	Built Area	179699×100/10,000	1797	91%
5	Bare ground	951×100/10,000	9.5	0%
6	Range land	2932×100/10,000	29	1%

LULC change detection, 2017-2024

The change detection matrix (Table 5) shows that built-up area increased by 22.78 ha (+1.28%), while water bodies decreased by 8.89 ha (−17.77%), trees by 13.11 ha (−13.99%), range land by 5.53 ha (−15.96%) and bare ground by 0.79 ha (−7.67%). Crops increased from 1.96 ha

to 7.50 ha (+282.65%); because the starting area is very small, this large percentage represents a small absolute change and, in a densely built-up setting, may reflect small patches of urban cultivation or classification differences at 10 m resolution rather than agricultural expansion

Table 5. LULC change detection matrix of 2017 and 2024.

LULC Class	2017 area (ha)	2024 area	Net change (ha)	Percentage change
Water	50.02	41.13	-8.89	-17.77%
Trees	93.73	80.62	-13.11	-13.99%
Crops	1.96	7.50	+5.54	+282.65%
Built-up	1,774.13	1,796.91	+22.78	+1.28%
Bare ground	10.30	9.51	-0.79	-7.67
Rangeland	34.64	29.11	-5.53	-15.96%

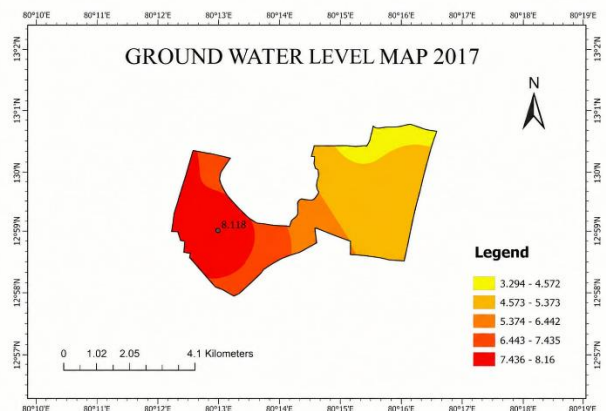
Groundwater depth in 2017

The IDW map for 2017 (Figure 5) shows depth to groundwater ranging from 3.294 m to 8.160 m (Table 6). The deepest water levels (7.436–8.160 m, very deep) occur in the western part of the study area around the Velachery observation point, where the depth was 8.1 m (8.118 m). This zone coincides with the continuously built-up western part of the LULC map (Figure 3), which has only a few small water bodies. Depths become progressively shallower towards the east and north-east, and the shallowest zone (3.294–4.572 m, very shallow) lies at the north-eastern edge near the Adyar estuary and coast, where tree cover and water are present in the LULC map. This spatial pattern suggests a possible association between dense built-up.

Table 6. Spatial classification of groundwater depth, 2017.

CLASS	GROUNDWATER RANGE (m)	DEPTH CATEGORY
1	3.294 – 4.572	Very Shallow
2	4.573 – 5.373	Shallow
3	5.374 – 6.442	Moderate
4	6.443 – 7.435	Deep
5	7.436 – 8.160	Very Deep

cover and greater depth to groundwater, although other factors such as abstraction and local geology were not examined.

**Fig.5:** Groundwater level (depth) map of Velachery, 2017 (IDW interpolation).

Groundwater depth in 2024

In 2024 (Figure 6) the depth to groundwater lies within a much narrower range of 3.250–4.406 m (Table 7). The greatest depth class (3.950–4.406 m) is again in the west, around the Velachery observation point, where the depth was 4.01 m, and a second area of relatively greater depth (3.6 m) appears near the coast at

the eastern observation point. The shallowest values (about 3.25–3.44 m) are found in the central and northern parts of the study area. The west–east gradient seen in 2017 is still present in 2024 but is much weaker.

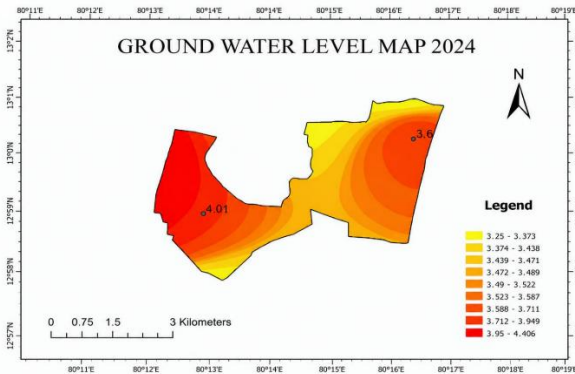


Fig.6: Groundwater level (depth) map of Velachery, 2024 (IDW interpolation).

Table 7. Spatial classification of groundwater depth, 2024.

CLASS	GROUNDWATER DEPTH RANGE (m)	CATEGORY
1	3.250 – 3.373	Very Shallow
2	3.374 – 3.438	Very Shallow
3	3.439 – 3.471	Very Shallow
4	3.472 – 3.489	Very Shallow
5	3.490 – 3.522	Very Shallow
6	3.523 – 3.587	Very Shallow
7	3.588 – 3.711	Shallow
8	3.712 – 3.949	Shallow
9	3.950 – 4.406	Shallow

Categories in Table 7 are relative to the 2024 range. On the 2017 scheme (Table 6), the whole 2024 range (3.250–4.406 m) would fall within the “very shallow” class (3.294–4.572 m).

Point-based groundwater depth change, 2017–2024

At the Velachery observation point the depth to groundwater was 8.118 m in 2017 and 4.010 m in 2024. Using $\text{Change} = 2024 \text{ depth} - 2017 \text{ depth}$, the change is $4.010 - 8.118 = -4.108 \text{ m}$ (Table 8), indicating a decrease in depth to groundwater, that is, a water level closer to the ground surface in 2024.

Table 8. Point-based groundwater depth change between 2017 and 2024.

Observation point	2017 Groundwater Depth (m)	2024 Groundwater Depth (m)	Change	Change Interpretation
Velachery	8.118	4.010	-4.108	Decrease in depth to groundwater

A second observation point in the eastern part of the study area recorded 3.6 m in 2024; no 2017 value is available for it, so no change could be calculated.

DISCUSSION

The LULC results are associated with increasing pressure on the surfaces that support recharge. Water bodies decreased by about 18%, tree cover by about 14% and range land by about 16%, while the already dominant built-up class expanded further. This is consistent with the general pattern reported for Chennai, where built-up growth and loss of water bodies were documented for the preceding decade (MuraliKrishna & Sahithi, 2023), and with modelling studies suggesting that urban expansion may reduce recharge in the city (Sadath et al., 2024).

The groundwater results show shallower water levels in 2024 than in 2017 at the monitored point and a much narrower depth range across the area. This does not by itself indicate that urbanization improves groundwater conditions. Depth to groundwater on a given date may be associated with antecedent rainfall, the season of measurement, pumping and nearby recharge sources as well as with land cover. A year following a poor monsoon and a year following a wet monsoon can differ strongly in groundwater depth regardless of land cover change. In addition, leakage from water supply and sewer lines in urban areas may raise water levels while degrading water quality (Lerner, 1990; Wakode et al., 2014, 2018). A comparison of two dates cannot separate these influences, so the results suggest a potential relationship between urban growth and groundwater conditions rather than establishing cause and effect. A longer time series with rainfall and abstraction data would be needed to test it.

What the study does indicate is that Velachery has very little natural surface remaining through which recharge can occur, and that even this small remainder is decreasing. In such a setting, groundwater levels may depend heavily on rainfall events and artificial sources, which may make them less resilient in dry years. The 2017 map, with depths exceeding 8 m in the densely built-up western sector, illustrates how deep-water levels can become under such conditions.

Impact of Urbanization on Water Resources

Urbanization can affect water resources through several linked pathways. The evidence from this study for each pathway, and its possible implication, is summarised in Table 9 and discussed below.

Table 9. Urbanization factors, evidence from Velachery and possible implications for water

Urban factor	Evidence from this study	Possible implication for water resources
Increase in impervious surface	Built-up area 1,774.13 ha → 1,796.91 ha (+1.28%)	May contribute to reduced infiltration and higher runoff, and thus to lower recharge from rainfall
Loss of water bodies	Water 50.02 ha → 41.13 ha (−17.77%)	Suggests reduced surface storage and seepage recharge, and less buffering of floods
Loss of vegetation and open land	Trees −13.99%; rangeland −15.96%; bare ground −7.67%	Associated with fewer permeable surfaces and greater heat and evaporation from paved areas
Demand and abstraction	Dense built-up cover across about 90% of the area	May be associated with greater dependence on groundwater and tanker supply in dry periods
Groundwater level variation	8.118 m → 4.010 m at the Velachery point; range narrowed to 3.250–4.406 m	Levels may be strongly influenced by rainfall and urban leakage, indicating possible vulnerability in dry years

Reduced infiltration and increased runoff

Paving and roofing seal the soil surface, so a larger share of rainfall may become runoff and a smaller share may infiltrate (Shuster et al., 2005). In a low-lying, flood-prone locality such as Velachery, increased runoff combined with intense north-east monsoon rainfall may raise the risk of flooding, and water that is drained away quickly is not available to recharge the shallow aquifer.

Loss of water bodies and green cover

Lakes, tanks, marshes and vegetated patches act as storage and recharge zones. The 17.77% decrease in water area and the 13.99% decrease in tree cover recorded here may have contributed to a loss of these functions. Although the absolute areas are small, they are among the few permeable and water-holding surfaces left in the study area, so each loss may have a proportionally larger effect on local recharge.

Increased demand and groundwater abstraction

Growth of population and commercial activity is associated with increased water demand. Where piped supply is inadequate, residents and businesses may turn to borewells and tanker water, and studies in Chennai and its peri-urban areas have linked such abstraction to lowered water levels and deteriorating water quality. In a coastal aquifer, sustained abstraction may also draw saline water inland. Abstraction data were not available for this study, so this pathway could not be tested.

Urban recharge and water quality

Leakage from supply pipes and sewers, and seepage from septic systems, may add water to the aquifer and raise water levels in some urban areas, but this water is often contaminated (Lerner, 1990; Wakode et al., 2014, 2018). Shallower groundwater in a densely built area therefore does not necessarily indicate healthy conditions. Groundwater quality analysis is needed alongside depth monitoring, especially close to the Adyar River and the coast.

Implications of planning

The results suggest that water resource management in Velachery could focus on protecting and restoring the remaining water bodies, maintaining permeable and green surfaces, and increasing artificial recharge through rainwater harvesting, recharge structures and permeable pavements. Regular monitoring of groundwater depth and quality at more observation wells, combined with periodic LULC mapping, would help detect changes early.

CONCLUSION

This study compared land use/land cover and groundwater depth in Velachery, Chennai, for 2017 and 2024 using 10 m Sentinel-2 based LULC data, GIS change detection and IDW interpolation. The area was already highly urbanised, and built-up land increased from 1,774.13 ha to 1,796.91 ha (+1.28%). The more notable change was in the remaining natural surfaces: water bodies decreased by 17.77%, tree cover by 13.99% and range land by 15.96%.

These decreases may have contributed to a reduced capacity for storage and natural recharge in the locality. Depth to groundwater at the Velachery observation point decreased from 8.118 m in 2017 to 4.010 m in 2024 (−4.108 m), and the interpolated depth range narrowed from 3.294–8.160 m to 3.250–4.406 m. Because groundwater depth is likely to be associated with rainfall, season and urban leakage as well as land cover, this result should not be taken to mean that urbanization has no adverse effect on water resources. Taken together, the LULC and groundwater results suggest a potential relationship between urban growth and pressure on water resources in Velachery, and they indicate that groundwater levels in a heavily built-up setting may depend strongly on external inputs.

The study has some limitations. Only two years were compared, the groundwater surfaces were interpolated from a small number of observation points, the season of measurement and rainfall were not controlled for, and the LULC maps were not independently validated with field data. Future work should use multi-year and seasonal (pre- and post-monsoon) groundwater data from more wells, rainfall records, an accuracy assessment of the LULC maps, and groundwater quality analysis. Even so, the combination of LULC mapping and groundwater depth mapping is a useful and low-cost way to identify possible water resource stress in rapidly urbanising localities, and the results support the protection of remaining water bodies and the promotion of recharge measures in Velachery.

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