

Assessment of Spatio-Temporal Changes in Groundwater Quality Using Water Quality Index and Its Irrigation Suitability in Puducherry Region, Southeast India

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Abstract

Groundwater sustains life in Puducherry coastal regions but faces threats from urbanization and land-use change. The study evaluated 70 groundwater samples in 2022, considering their suitability for drinking and irrigation purposes using water quality index, Canadian council of ministers of the environment-water quality index, and irrigation indices like sodium adsorption ratio, Percent Sodium, permeability index, Kelly's ratio, and residual sodium carbonate. Sentinel-2A satellite images indicated that urban areas increased from 104.7 km² (35.1%) in 2010 to 105.7 km² (35.4%) in 2024, while agricultural land decreased marginally, mirroring urban pressure. Approximately 77.1% of the groundwater samples belonged to Fair to Marginal categories for drinking, and just 1.4% was rated Excellent under Canadian Council of Ministers of the Environment-Water Quality Index. Salinity and nitrate were of primary concern, particularly in urbanised areas such as Solai Nagar and Kuruchikuppam, where water quality had been rated as Poor. For irrigation, 57.1% of pre-monsoon and 65.7% of post-monsoon samples were of the C3S1 class, reflecting low sodium hazard but high salinity, whereas 4.3% of pre-monsoon and 1.4% of post-monsoon samples encountered medium sodium hazard with very high salinity (C4S2). Kelly's Ratio was greater than 1 in 21.4% of pre-monsoon and 34.3% of post-monsoon samples, reflecting sodicity risks, while 98% of the samples had safe residual sodium carbonate values less than 2.5 meq/L. Regions with high urbanisation or intensive farming always exhibited high sodium adsorption ratio, Percent Sodium, and electrical conductivity, affirming a real correlation between land-use/land cover patterns and decreasing groundwater quality. To prevent these risks, the study suggests combined land-water planning, strict wastewater control, and the promotion of sustainable irrigation practices to ensure Puducherry's water resources and agricultural yield.

Keywords: Water Quality Index, Salinity Hazard, Land-Use, Land cover, Remote Sensing, Puducherry

Introduction

Groundwater is a vital resource with considerable importance and is a source of drinking water worldwide (Das and Nag, 2022). The increasing population, coupled with rapid urbanization, agricultural intensification, and land use/land cover (LULC) changes, has significantly intensified the demand for freshwater resources (Mishra, 2023), in dry, semi-arid, and isolated rural regions where groundwater is heavily relied upon for household, agricultural, and potable needs (Makki *et al.*, 2021). In these areas, dependence on groundwater becomes even more pronounced during droughts, when surface water supplies are scarce (Adimalla *et al.*, 2020; Dube *et al.*, 2020). Investigating land suitability for irrigation is a crucial aspect of multi-objective planning in developing and managing water resource projects involving irrigation. The availability of irrigation often drives

changes in land use and encourages more intensive cropping practices. However, the mismanagement or improper application of irrigation water can lead to environmental degradation, reducing land productivity and compromising its quality for future agricultural use (Kumar *et al.*, 2002).

In recent years, Water Quality Index (WQI) models have gained popularity for evaluating both surface and groundwater quality, as they offer a more simplified and accessible approach compared to traditional methods (Aljanabi *et al.*, 2021). These models transform various water quality parameters into a single, unitless numerical value that effectively represents the overall water quality status (Sutadian *et al.*, 2016). Groundwater is highly vulnerable to contamination from various human activities, including mining, intensive farming, urban expansion, and industrialisation (Chen *et al.*, 2023; Schwarzenbach *et al.*, 2010). Deterioration in water quality poses a serious risk to public health (Fida *et al.*, 2023). The association between LULC and water quality can differ depending on the spatial scale of analysis (Tanaka *et al.*, 2016). Recent studies in landscape ecology and forecasting

have emphasised the part of landscape spatial structure in exploring relations between LULC and water quality across several gauges (Alberti *et al.*, 2007; Joji and Saha, 2026). The rapid expansion of urban areas has led to a complex interplay between intensified LULC changes and groundwater quality, creating a range of environmental encounters (Acharya *et al.*, 2023). In Pakistan- especially in the Sargodha region- groundwater sources have become increasingly vulnerable over recent decades due to accelerated industrialisation, mining, agriculture, and urban development. These activities have significantly affected both the quality and availability of groundwater (Baloch *et al.*, 2022). Urbanisation and LULC dynamics play a crucial role in influencing groundwater quality, particularly in metropolitan regions where human activities are highly concentrated (Subba Rao *et al.*, 2019; Jia *et al.*, 2018; Jeenu *et al.*, 2025). He and Wu (2019) outlined a three-step framework for examining the affiliation between groundwater quality and LULC: (1) assessing groundwater quality using a specific methodology; (2) identifying the LULC characteristics of the study area; and (3) linking the groundwater quality index to the observed LULC.

The main objective of the study includes (1) to assess the spatial and temporal variations in groundwater quality in the Puducherry region using the Water Quality Index (WQI), (2) To evaluate the suitability of groundwater for irrigation purposes by analysing key hydrochemical parameters and applying irrigation-specific indices and (3) To analyse the relationship between groundwater quality and LULC variations, with emphasis on their influence on groundwater characteristics.

Geomorphology and Geology of the Study Area

Puducherry is located on the Coromandel Coast between 11°45' and 12°03' North lat. and 79°37' and 79°53' East long., covering an area of 294 km² (Fig. 1). It lies within Pambai Watershed and comprises 164 inhabited settlements, organized into five communes. Surrounded on three sides by South Arcot district of Tamil Nadu and bordered by the Bay of Bengal to the east. Puducherry is situated about 162 kms south of Chennai. The surrounding region includes the South Arcot Taluks of Cuddalore, Villupuram, and Tindivanam. The terrain of Puducherry is largely a peneplain, with an elevation of 15 meters above mean sea level. It features three primary physiographic zones: uplands, alluvial plains, and littoral plains (Thilagavathi *et al.*, 2020). The coastal plain is a narrow strip stretching approximately 22 kms along the Bay of Bengal, with widths ranging between 400 and 60m. Northern sections of the littoral area show significant beach erosion (Chidambaram *et al.*, 2018). The general topography of Puducherry resembles that of coastal Tamil Nadu.

Hydrologically, the area is dominated by the drainage systems of the Gingee and Pennaiyar Rivers, along with other smaller streams, which are interspersed with lakes and reservoirs across deltaic regions (Thilagavathi *et al.*, 2012). Puducherry's monsoon pattern is distinct from much of India, with rainfall typically occurring from July to September and again from November to January. Like other coastal areas, it experiences high humidity level. May and early June are the coolest periods, with average minimum temperatures around 27°C, though max. temp. can soar above 43°C. The lowest recorded temperature is approximately 11.1°C. Most of the region's rainfall results from cyclonic storms that develop over the Bay of Bengal during the

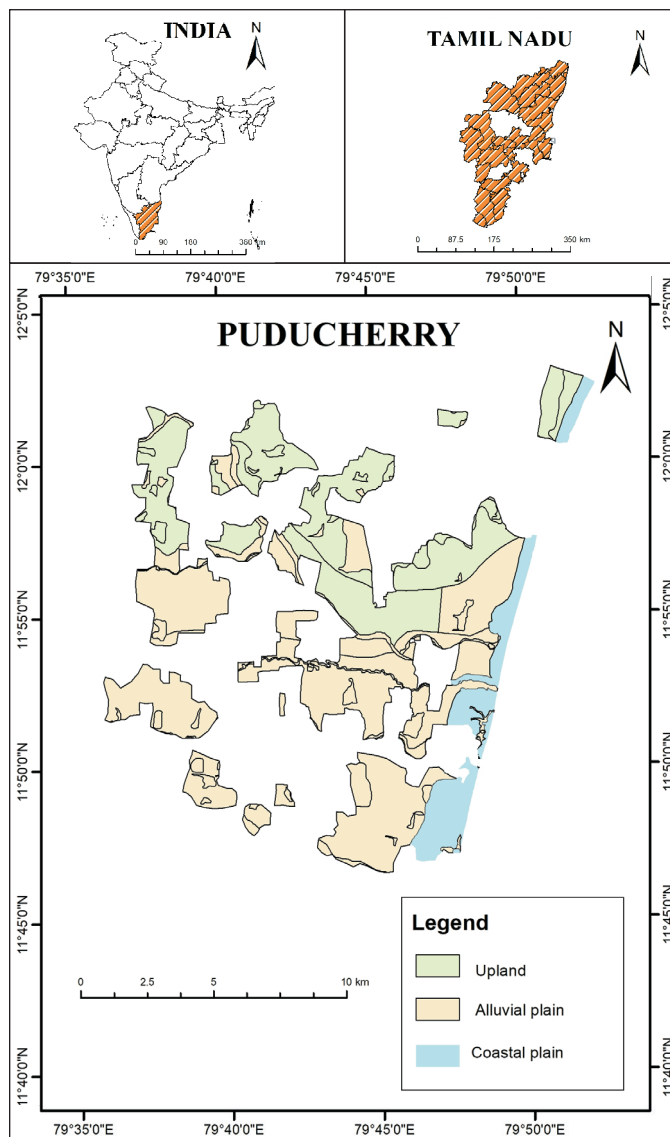


Fig. 1. Location Map of the Puducherry Region

northeast monsoon. The area obtains mean annual precipitation of 1,383 mm. Geologically, the region consists of unconsolidated and semi-consolidated sediments underlain by Archaeans and these sloping towards the sea (Susan *et al.*, 2025). These formations fall into two main hydrogeological categories: porous sedimentary rocks and fractured crystalline rocks. Groundwater in the region is heavily exploited, with tube wells being the only structures.

Materials and Methods

A total of 70 water samples were collected from several sites across Puducherry. The samples, drawn from tube wells ranging in depth from 20 to 100 meters below ground level (mbgl), were carefully collected using 1-litre HDPE bottles. In-situ parameters were measured on-site, and the samples were subsequently transported to the laboratory to analyse different cations and anions. In the laboratory, parameters like pH, EC, total hardness (TH), TDS, and major ions were analyzed. The pH, EC, and TDS were measured by pH meter and an EC meter. Major cations were identified using an ICP-mass spectrometer. Total hardness was

determined through complexometric titration with ethylenediaminetetraacetic acid (EDTA). Sulfate (SO₄) concentrations were measured using a spectrophotometric method, nitrate (NO₃) was analyzed by ion chromatography, and chloride (Cl) levels were determined via volumetric titration using AgNO₃ and K₂Cr₂O₇. Bicarbonate (HCO₃) and carbonate (CO₃) concentrations were assessed through titration techniques employing HCl, phenolphthalein, and methyl orange indicators. The results were evaluated against the WHO (2022) drinking water standards. To evaluate the accuracy of the chemical analysis, ion balance error (IBE) was calculated using the concentrations of major cations (Ca²⁺, Mg²⁺, Na⁺, and K⁺) and anions (HCO₃⁻, Cl⁻, SO₄²⁻, and NO₃⁻), expressed in milliequivalents per litre (meq/L), using the following equation:

$$IBE (\%) = (\sum \text{Cations} - \sum \text{Anions} / \sum \text{Cations} + \sum \text{Anions}) \times 100$$

The majority of the samples fall within the acceptable charge balance error limit of ±5%, while a few samples fall within ±10%, indicating satisfactory analytical accuracy and reliability of the hydrochemical data. The irrigational suitability is determined using the equations, which are described in Fig. 2.

The Remote Sensing data was obtained from the European Space Agency's Sentinel-2A mission, which provides high-to-moderate spatial resolution imagery (10–60 m) across 13 spectral bands. In the work, eight key parameters were chosen to compute the WQI (pH, EC, TDS, Ca, Mg, Cl, Na and K), following standards set by the WHO (2022), BIS (2012), and Indian Council for Medical Research (ICMR) (1975). The weighted arithmetic index method (Brown *et al.*, 1972) was applied for WQI determination, which involves two major steps: determining Quality Rating (or Sub-Index) and Unit Weight. The advanced level WQI is investigated by using the CCME-WQI. The methodology for both is presented in the flow chart (Fig. 2).

Results and Discussion

Irrigation Suitability

The kind, quality, and amount of water all significantly impact plant growth. Crop yields can be decreased in farming when water quality is poor (Iqbal *et al.*, 2012). In particular, chemical fertilisers, pesticides, and insecticides used in intensive agricultural practices can significantly impact the groundwater quality. Many indications are taken into consideration when determining whether groundwater is fit for irrigation, such as Salinity Hazard, Kelly's Ratio, Permeability Index (PI), Sodium Adsorption Ratio (SAR), Percent Sodium (%Na), and Residual Sodium Carbonate (RSC).

The SAR is used to assess the relative activity of Na⁺ ions compared to calcium and magnesium ions in soil exchange processes, making it critical for finding the aptness of water for irrigation purposes (Haritash *et al.*, 2014; Iqbal *et al.*, 2012). The decline in crop health and the deterioration of soil structure in the irrigation water is caused by the presence of high levels of Na⁺. In the USSL diagram, which categorising the irrigation water quality, the SAR values are plotted against the EC. In the present study most of the samples in the both season (pre monsoon (PRM) and post monsoon (POM)) were coming under C3S1 (low SAR and high EC) and C2S1 (low SAR and medium EC). About 4.3% and 1.4% of PRM and POM groundwater samples are considered unsuitable for irrigation as they are representing the of medium sodium hazard with very high salinity (C4S2). Because the water intake of the plants is hindered by the increased osmotic pressure and soil degradation by the potential Na⁺ (Brindha and Elango, 2011; Ramesh and Elango, 2011). Analysing the data further, 81.4% of PR and 78.6% of POM groundwater samples had EC values within the permissible limits, while Na⁺ concentrations were permissible in

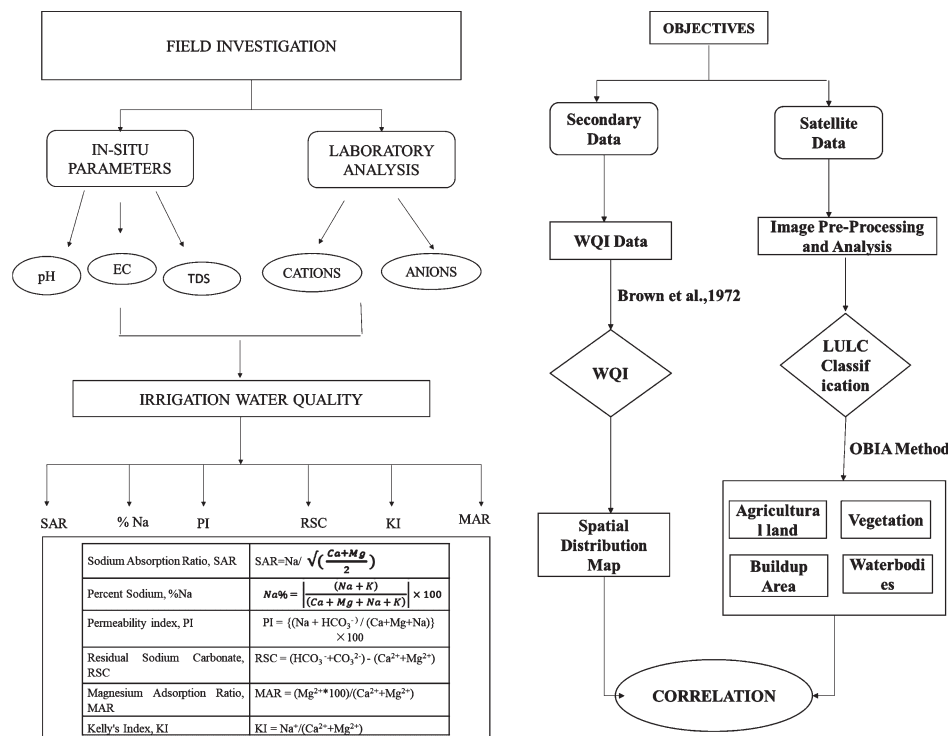


Fig. 2. Methodology for computing the Irrigational Suitability and WQI

74.3% of PRM and 92.9% of POM samples. The detailed USSL classification of groundwater quality showed that C1S1 (low SAR and low EC) conditions were observed in 1.4% of PRM and 4.3% of POM samples, C2S1 (low SAR and medium EC) in 22.9% and 18.6% of samples respectively, and C3S1 (low SAR and high EC) dominated with 57.1% of PRM and 65.7% of POM samples, with a smaller percentage falling under C4S2, indicating medium SAR and very high EC conditions (Fig. 3).

The concentration of Na⁺ in water is evaluated using the Percent Sodium (%Na), which is crucial as high Na⁺ levels can reduce soil permeability and affect soil structure (Kelly, 1951; Wilcox, 1955). The results based on Wilcox's classification indicated that during the PRM, 37.1% of groundwater samples fell under the good to permissible category for irrigation use, 35.7% as excellent, 14.3% doubtful, and 1.4% unsuitable (Fig.3). During the POM, 40% were classified as excellent, 20% good to permissible, 14.3% doubtful, and 2.9% unsuitable for agricultural use. The permeability of the soil, influenced by prolonged irrigation with such water, was assessed using PI method after Doneen, which considers the effects of ions like Na⁺, HCO₃⁻, Ca²⁺, and Mg²⁺ on soil permeability. The study found that most of the groundwater samples fell within Classes 1 and 2 (Fig. 3), indicating moderate suitability for irrigation, aligning with findings from Chidambaram et al. (2011, 2015).

Residual Sodium Carbonate (RSC) is another critical factor for irrigation water assessment, as it indicates the potential for Na⁺ build-up in soils. A negative RSC value suggests that Ca²⁺ and Mg²⁺ are present in sufficient quantities to counteract the effects of Na⁺, thus posing minimal risk of soil degradation. Conversely, a positive RSC value implies that bicarbonate and carbonate ions are likely precipitating calcium and Mg²⁺, increasing the risk of Na⁺ accumulation (Sagar, 2015; Raju, 2007; Fig. 3). It is generally accepted that water with an RSC exceeding 2.5 meq/L is unsuitable for irrigation (Wilcox et al., 1954). In the present study the risk due to the accumulation of Na⁺ is nominal, as 98% of the groundwater samples show negative RSC values.

Finally, Kelly's Ratio (KR) was utilized to further evaluate the suitability of irrigation water and represents the ratio of Na⁺ to the total of Ca²⁺ and Mg²⁺ concentrations and indicates the predominance of Na⁺ in the exchange complex of the soil (Kelly, 1940; Karakus and Yildiz, 2020). A value for KR that is less than 1 indicates that Ca²⁺ and Mg²⁺ are adequate to support soil structure, whereas a KR value > 1 indicates that Na⁺ will most probably predominate, resulting in soil degradation as well as reduced permeability. In the investigated area, 21.4% of PRM and 34.3% of POM samples with KR > 1, which means that a large percentage of the water sources have the potential risk of causing long-term agricultural contamination because of Na⁺ buildup and its negative effect on soil health.

CCME-WQI

The study brought out considerable variation in the quality of groundwater throughout the area (Fig. 4). There was just one sample, that of Pillaichavady (PW4), which was graded as "Excellent," 1.4% of the total, which was almost pristine water with no major concerns. Eleven samples (15.7%), such as Ganapathichettikulam (PW1 and PW2), Sellipet (PW6), Kunichampet (PW10), and Villupuram (PW26), were scored as "Good," indicating safe drinking water overall with slight concerns. Most, 29 samples (41.4%), were

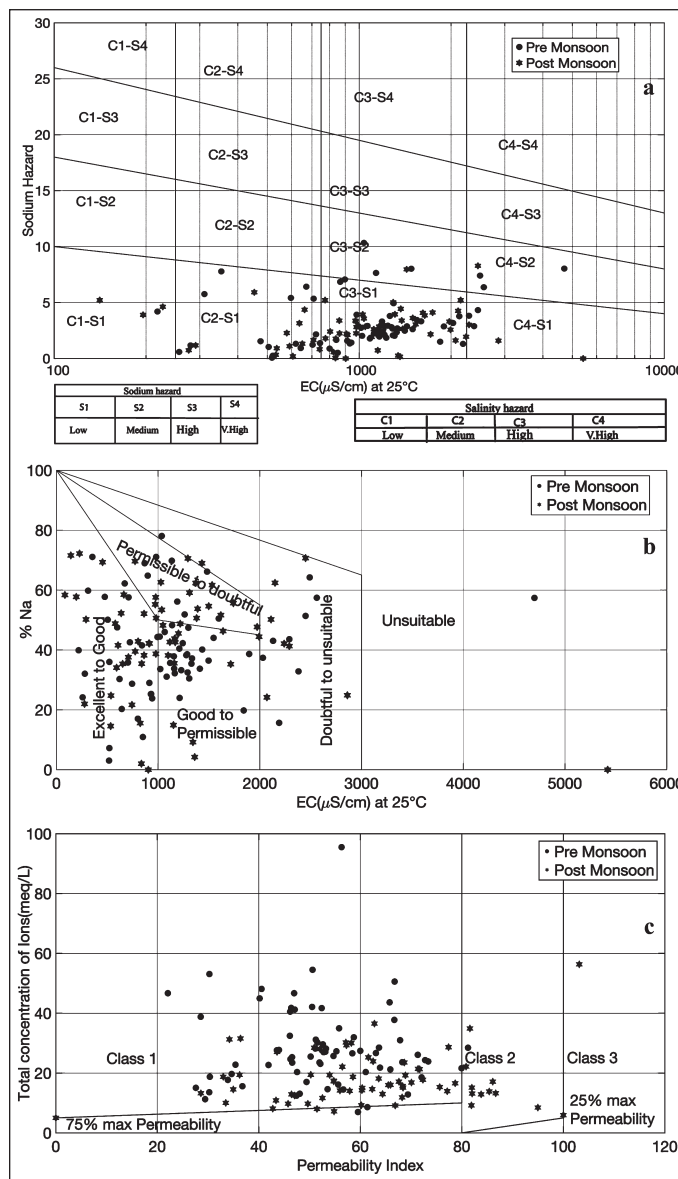


Fig. 3. (a) USSL classification, (b) Representation of %Na in Wilcox diagram and (c) Doneen's Permeability Index classification of hydrochemistry of the study area

classified as "Fair" in the range of areas including Mutrampattu (PW9), Thirukkanur (PW11), and Villupuram (PW28), where water is safe but there are occasional exceedences. Approximately 25 samples (35.7%) were graded as "Marginal," with frequent standard violations being reported at places such as Ammamamkuppam (PW5), Vinayagampattu (PW7), and Nerkunam (PW8), meaning they should be treated before use. More seriously, four samples (5.7%) from Solai Nagar (PW16), Kuruchikuppam (PW54), Edayarpalayam, and Kirumampakkam belonged to the "Poor" category, indicating severe contamination and unsafety for drinking without significant treatment. Spatial analysis indicated that more than 77.1% of samples were in the "Fair" and "Marginal" categories, indicating prevalent water quality issues throughout the area (Table 1). Specific areas like Solai Nagar and Kuruchikuppam exhibited "Poor" water quality, likely due to localised pollution from domestic wastes, agricultural runoff, or industrial discharges. In many locations, including Thengaithittu, Netaji Nagar, and

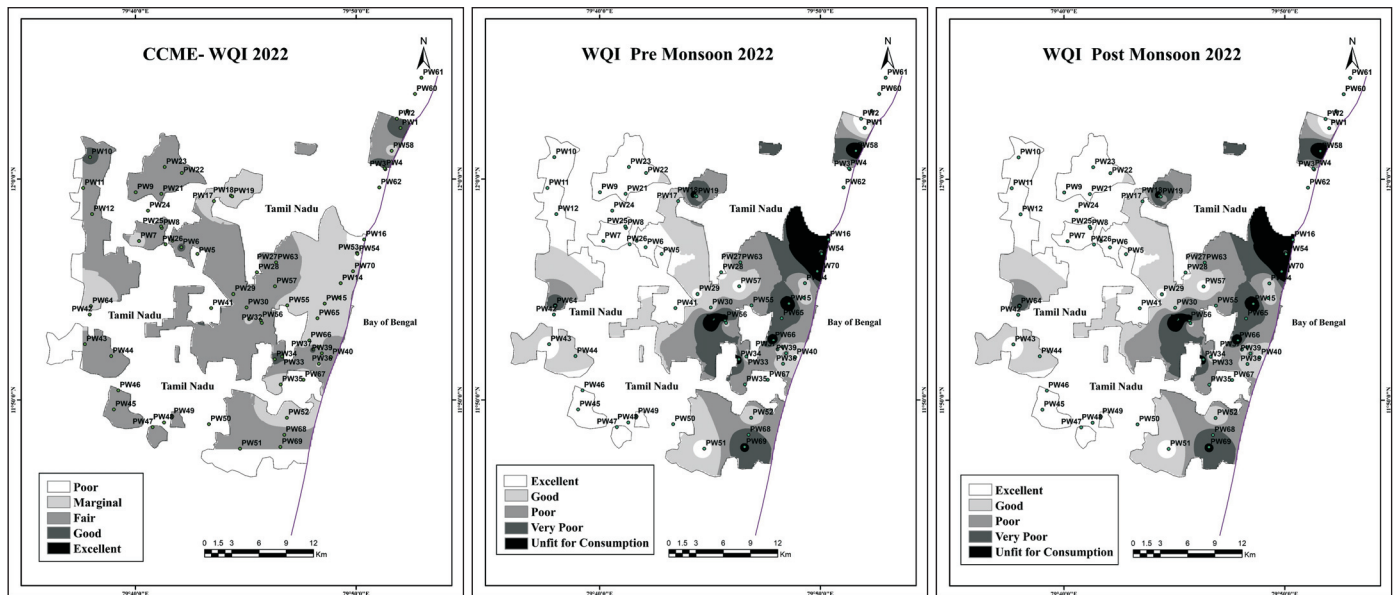


Fig. 4. Thematic layer of CCME-WQI and WQI for Pre and Post Monsoon Seasons

Santhikuppam, repeated exceedances of parameters like TDS, nitrate, and microbial contaminants were observed, attributed to anthropogenic influences like LULC changes, overextraction, and poor wastewater management practices.

Water Quality Index (WQI)

The WQI is a composite measure that reflects the inclusive quality of water by integrating various parameters. It is crucial for evaluating the aptness of water for drinking, irrigation, and general use. The 2022 WQI data for PRM and POM categorize sites as Excellent (0-25), Good (51-75), Poor (26-50), and Very Poor (76-100) (Fig. 4, Table 2). A comparison between WQI of PRM and POM shows notable changes in water quality. Many sites remained in the “Excellent” or “Good” categories, but some samples showed improvement or deterioration. During PRM, most sites were rated “Excellent” or “Good,” while a few were “Poor” and marked unfit for consumption. POM data revealed both positive shifts, due to dilution and natural recovery, and negative shifts, likely caused by runoff from agricultural, urban, or industrial areas.

Some sites improved between seasons, while others declined,

indicating spatial and seasonal variability. Locations with consistently “Poor” or “Very Poor” quality are of particular concern, pointing to chronic pollution issues. In POM, there was a slight increase in “Excellent” sites, while “Good” and “Poor” sites slightly decreased. “Very Poor” sites remained unchanged. Recommendations include detailed investigations of critical sites, pollution source control, continued monitoring, and public engagement. Expanding parameter analysis and studying monsoon impacts through predictive models can aid future planning. For unfit locations, remedial actions and alternative water sources are essential.

Land Use Land Cover, LULC

Analysis of LULC data from 2010 to 2024 (Table 3) reveals significant changes across four key land cover types: water, developed, barren, and agriculture (planted/cultivated land). In 2010, developed land was prominent (35.10%), closely followed by planted/cultivated land (37.26%). Barren land accounted for 22.62%, and water bodies made up just 5.02%. By 2015, water bodies expanded to 6.55%, but developed land declined to 29.77%, barren land increased to 29.33%, and agricultural land reduced to 34.35%, indicating a shift possibly driven by environmental or land use pressures. In 2020, developed areas rebounded to 31.29%, and planted/cultivated land increased significantly to 40.79%, becoming the dominant category. Barren land decreased to 23.25%, and water bodies shrank to 4.67%. This suggests a recovery in both urban and agricultural lands, likely at the expense of barren and water areas. By 2024, developed land grew further to 35.42%, again taking the lead. Planted/cultivated land remained substantial at 39.53%, while barren land declined to 19.54%, and water areas slightly increased to 5.51%. Overall, Puducherry’s landscape has seen steady urban expansion, a decline in barren land, and sustained agricultural activity over the years, alongside fluctuations in water bodies. These trends reflect the ongoing influence of both development pressures and environmental factors, illustrating a dynamic interaction between human use and natural systems in this coastal region.

Table 1: Classification of water samples based on CCME-WQI

CCME WQI	Ranking	No. of Samples	Percentage of Samples
95-100	Excellent	1	1.4
80-94	Good	11	15.7
65-79	Fair	29	41.4
45-64	Marginal	25	35.7
0-44	Poor	4	5.7

Table 2: Classification based on WQI by Brown et al. (1970)

Ranking		No of samples		Percentage	
WQI	WQI Status	pre	post	pre	post
0-25	Excellent	38	47	54.3	67.1
26-50	Good	8	10	11.4	14.3
51-75	Poor	3	3	4.3	4.3
76-100	Very poor	4	0	5.7	0.0
>100	Unfit for consumption	17	8	24.3	11.4

Table 3: Analysis of LULC data from 2010 to 2024

LULC	Area (sq.km)	Percentage
2010		
Water	14.968292	5.017856607
Developed	104.712735	35.10310255
Barren	67.488611	22.62436974
Planted / Cultivated	111.130875	37.2546711
2015		
Water	19.528922	6.546565632
Developed	88.817397	29.77373348
Barren	87.499851	29.33206028
Planted / Cultivated	102.461723	34.34764061
2020		
Water	13.931385	4.67002286
Developed	93.360183	31.29582513
Barren	69.355222	23.24897863
Planted / Cultivated	121.668345	40.78517337
2024		
Water	16.425514	5.506206922
Developed	105.662507	35.42048227
Barren	58.303559	19.54468275
Planted / Cultivated	117.917478	39.52862806

Relationship of LULC with Groundwater Quality and Irrigation Suitability

The relationship between land use/land cover (LULC) and groundwater quality of Puducherry indicates distinct spatial and temporal differences in CCME-WQI, WQI, and irrigation suitability indices. Urbanization has brought domestic waste, industrial effluents, and poorly treated sewage into aquifers, giving rise to Poor to Marginal quality classes dominating the scores and localized Very Poor scores, as found elsewhere with urbanization-associated groundwater degradation (Giri and Qiu, 2016; Xu and Zhang, 2020; Putra *et al.*, 2021). Agricultural soils further compromise quality by leaching nitrate, phosphate, and pesticides, yielding high the CCME-WQI and WQI parameter frequent exceedances (Sundaray *et al.*, 2016; Nathan *et al.*, 2012). Monsoon runoff enhances these impacts by carrying pollutants from agricultural and urban soils, with sporadic dilution due to rainfall and associated water bodies improving water quality at some locations (Pethaperumal *et al.*, 2008; Venkatesan and Singarasubramanian, 2014).

For irrigation, LULC-induced contamination is expressed as salinity, Na⁺ enrichment, and shifted ionic balances that have a direct bearing on such indices as SAR, %Na, RSC, PI, and KR (Richards, 1954; Ayers and Westcot, 1985). Urban effluents and road runoff impart dissolved salts and heavy metals, while fertilizer application and irrigation return flows increase EC, nitrate, and agrochemical levels, decreasing soil permeability and crop suitability (Spalding and Exner, 1993; Follett, 1989). Coastal hydrological processes, especially saline seawater intrusion, enhance Na⁺ risks, whereas freshwater discharge variations regulate irrigation suitability (Custodio and Bruggeman, 1987). The current groundwater condition-Fair to Poor for potable use and progressively unsuitable for irrigation-thus reflects the collective impact of increasing developed lands, increased cultivation, poor wastewater handling, and coastal processes. These results emphasize that sustainable groundwater utilization in Puducherry is a call for integrated water and land use, emphasizing

specifically urban effluent regulation, agriculture, and saltwater intrusion.

A Pearson correlation analysis was conducted to examine the relationship between land use and land cover (LULC) and groundwater quality, utilizing a semi-quantitative LULC classification. The results (Table 4) show that LULC is strongly linked to salinity-related factors like Cl ($r = 0.70$), TDS ($r = 0.68$), and EC ($r = 0.65$). This shows how urban and coastal land uses affect salinity. A moderate positive correlation with NO₃ ($r = 0.55$) indicates agricultural influences. The negative correlation between NO₃ and EC ($r = -0.40$) indicates that nutrient contamination and salinity derive from distinct sources. These results quantitatively substantiate the impact of LULC on groundwater quality. The analysis is based on dominant LULC categories rather than percentage-based extraction and therefore represents indicative relationships.

Conclusions

The study deals with the combined evaluation of groundwater quality and suitability for irrigation purposes in relation with LULC changes in the Puducherry region for 2022. The seasonal variation and long-term trends affecting groundwater resources are identified by using the quality indices such as CCME-WQI, WQI and irrigation parameters like SAR, %Na, PI, KR and RSC. The LULC pattern analysis indicated a considerable change in the landscape, characterized by a remarkable increase in developed land and corresponding reductions in agricultural land and natural cover. The processes of urbanization, industrial growth, and tourism development are primarily responsible for these changes, leading to lower natural recharge capacity and higher hazard of groundwater pollution through impervious surface area and unchecked anthropogenic discharge. Groundwater quality analysis across PRM and POM shows overall decline in water quality over time, especially in regions undergoing rapid land cover change. CCME-WQI and WQI values support a trend of shifting groundwater classes from good/moderate to marginal/poor classes, which is of concern regarding its suitability for drinking and household purposes. In addition, the assessment of irrigation suitability indices clearly indicates that a significant amount of groundwater is decreasing in suitability for agricultural use. Increasing values of SAR, %Na, and RSC point to the fact that salinity and sodicity hazards are increasingly becoming problems, which can reduce soil permeability and crop yields. These effects are especially high in regions where agriculture is still being carried out in the midst of creeping urbanization. The findings highlight the intricate interplay between LULC patterns and groundwater sustainability. The continuous spatiotemporal urban sprawl trend continues to pose a great threat to groundwater quality and usability in the region,

Table 4: Correlation Matrix of Hydrochemistry and LULC of the Region

	LULC	EC	TDS	NO ₃	Na	Cl	WQI
LULC	1	0.65*	0.68*	0.55*	0.62*	0.7*	0.6
EC	0.65*	1	0.99*	-0.4**	0.8*	0.85*	-0.3**
TDS	0.68*	0.99*	1	-0.42**	0.82*	0.88*	-0.28**
NO ₃	0.55	-0.4**	-0.42**	1	0.35	0.4	-0.33**
Na	0.62*	0.8*	0.82*	0.35	1	0.75*	-0.2**
Cl	0.7	0.85*	0.88*	0.4	0.75*	1	-0.32**
WQI	0.6	-0.3**	-0.28**	-0.33**	-0.2**	-0.32**	1

* Good correlation ($r > 0.6$; bold) ** Poor correlation ($r < 0$)

highlighting the paramount importance of rational water and land resource management policy. With LULC planning integrated with groundwater protection measures, stricter pollution control, and promoting the implementation of water-saving strategies are essential steps in mitigating adverse impacts and ensuring long-term water security in Puducherry.

Authors' Contributions

RSJ: Conceptualization, Investigation and Writing Original Draft. **JVS:** Data Curation, Visualization, Reviewing and Editing. **MS:** Formal Analysis, Reviewing and Supervision. **ASVNVK:** Methodology, Software, Validation. **DAS:** Resources, Data

Curation, Field Investigation. **RPB:** Resources, Data Curation, Field Investigation.

Conflict of Interests

The authors do not have any competing interests.

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