



RESEARCH ARTICLE

# Saltwater intrusion and soil salinisation in the coastal area of Chengalpattu district in Tamil Nadu

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## Abstract

Chengalpattu has been an agriculturally based coastal district in Tamil Nadu with a major land area under paddy cultivation. Here, the major environmental challenges are soil salinisation and saltwater intrusion, which affect the area's agricultural productivity. This study reports an integrated analysis of climate-driven soil salinisation in the Chengalpattu district of Tamil Nadu, using a multi-dataset analytical approach covering the period of 2013–24. Seven institutional secondary datasets comprising approximately 8300 records have been synthesised to examine the interactions across the rainfall, groundwater, surface water, soil and crop production systems. Rainfall variability has been analysed using long-term mean statistics and the Mann-Kendall trend tests, groundwater hydrochemistry, water table dynamics and soil salinity pattern have been evaluated using descriptive and non-parametric statistical methods. Results indicate extremely high inter-annual rainfall variability with a CV 49.5 %, including five deficit rainfall years during the study period. Groundwater quality of 643 station-year records from 2015–23 has indicated a mean electrical conductivity (EC) value of 1032  $\mu\text{S}/\text{cm}$  (marginal) with chloride ranging from 121–216 mg/L. Mann-Kendall analysis has revealed a significant declining water table trend where the  $\tau = -0.818$ ,  $Z = -3.43$  and  $p < 0.001$  with depth reducing from 6.90 m below ground level (mbgl) in 2013 to 3.35 mbgl in 2021, a net rise of 3.55 m. Surface water EC has increased from 212  $\mu\text{S}/\text{cm}$  in 2015 to 1013  $\mu\text{S}/\text{cm}$  in 2022, where the  $\tau = 0.6411$ ,  $p = 0.029$ , while shallow dug-well EC averaged 1521  $\mu\text{S}/\text{cm}$ , of 47 % higher than bore wells, indicating greater vulnerability of shallow aquifers. Soil analysis of 4617 samples has shown 59.9 % non-saline, 32.6 % slightly saline, 6.2 % moderately saline and 1.3 % highly saline soils. Rice cultivating areas have declined by 52.3 % from 97738 ha in the year 2015–16 to 49917 ha in the year 2022–23, with yield ranging from 3.55 – 4.97 t/ha. These findings highlight increasing salinisation risk and emphasise the need for proactive groundwater management, soil health restoration and adaptation of salt-tolerant crops in the coastal agricultural system.

**Keywords:** annual rainfall; groundwater quality; long-term mean; Mann-Kendall trend; multi-dataset; salinity pattern

## Introduction

Soil salinisation has been widely recognised as one of the most significant forms of land degradation in coastal agricultural systems worldwide (1, 2). Globally, approximately 833 million hectares are salt-affected soils, with secondary salinisation advancing at an estimated rate of 1 to 3 million hectares annually. In South Asia, the problem had been low-lying coastal plains, where the dual mechanism of saltwater intrusion resulting from rising sea levels and in situ salinisation was driven by severe evapotranspiration and shallow saline groundwater operating simultaneously (3, 4). The Coromandel coast of Tamil Nadu had represented a geographical zone where these pressure conditions of elevated climatic uncertainty had been intensified (5).

Chengalpattu district, located in the Southeastern Coast of Tamil Nadu, lies between 12° 14'00" N to 13° 02'00" N Latitude, 79° 31'30" E to 80° 15' 30" E Longitude. The district had been

bounded to the east by the Bay of Bengal and lies within the semi-arid tropical climate zone. It had supported an agricultural economy dominated by rice cultivation, which had constituted the dominant cropping system. The agricultural production in this region had primarily depended on the rainfall received from the Northeast and Southwest Monsoon and shallow alluvial aquifers. This district had been increasingly exposed to several interacting environmental stresses, unpredictable rainfall with a CV exceeding 49 %. Simultaneously, the shallow coastal aquifers are vulnerable to salt intrusion from the adjacent marine environment, intensifying the anthropogenic groundwater extraction. It had depressed the water table and amplified hydraulic connectivity. These conditions of Chengalpattu District are considered as an important case study area for examining the climate-induced salinisation process in the coastal regions of India (6, 7).

Despite the vulnerability, systemic multiparameter assessments integrating rainfall variability, groundwater quality,

water table dynamics, soil salinity and agricultural response over a long temporal scale remain limited. Most studies had focused on isolated parameters and had been restricted to a short temporal time limit, thereby limiting the ability to identify the long-term trends. The lack of an integrated and statistically rigorous assessment hindered the development of effective evidence-based and adaptive policy responses.

We hypothesised that: (i) groundwater quality and water table dynamics in Chengalpattu District exhibit statistically significant deteriorating trends over the study period, consistent with progressive saltwater intrusion driven by declining freshwater recharge and increasing abstraction pressure; and (ii) the observed spatial patterns of soil salinisation and the temporal decline in rice cultivated area are associated with these hydrochemical and hydrological changes representing a measurable agronomic consequence of coastal salinisation.

This study addressed the gap through a comprehensive secondary data integration approach, which assembles seven institutional datasets that compile approximately 8300 individual records across 2013–24. The objectives of the study were: (i) to quantify inter-annual rainfall variability and identify deficit and excess years relative to the long-term climatological average, (ii) to characterise groundwater hydrochemistry and classify irrigation suitability status, (iii) to test for statistically significant trends in water table depth using non-parametric methods, (iv) to examine the rainfall-groundwater salinity relationship, (v) to characterise soil salinity distribution across eight administrative blocks and (vi) to assess the decade-long trajectory of rice cultivated area and yield. Collectively, the findings were intended to provide an integrated understanding of the salinisation system and to identify spatial and temporal hotspots requiring priority intervention.

## Materials and Methods

### Study area

Chengalpattu District lies within the Coromandel coastal plains of Tamil Nadu. A low-lying, predominantly flat terrain with elevations below 30 m above mean sea level. Several draining rivers that flow eastward, including tributaries of the Palar and Cheyyar systems. These rivers traversed the district before discharging into the Bay of Bengal, which creates alluvial corridors. These alluvial corridors supported intensive rice cultivation. The principal geological formations contain Quaternary alluvial deposits that overlay the Archaean crystalline basement rocks. The shallow unconfined aquifers within the alluvium had been recharged primarily by monsoon rainfall and were hydraulically connected to the marine environment through the tidal stream estuaries and coastal

wetlands. The study area is shown in Fig. 1.

The district experienced a bimodal rainfall pattern. The northeast monsoon (October–December) was the major provider, accounting for approximately 55–65 % of the total annual rainfall, while the southwest monsoon (June–September) contributed a secondary but significant proportion. The grid point of the long-term annual rainfall of this study was located at 12.35° N, 79.86° E and had recorded 1161.2 mm of rainfall during the study period of 2013–23. This district has been classified as a semi-arid with a potential evapotranspiration that gradually exceeds the precipitation during the dry season (January–May). During this period, the saline groundwater rose through capillary action and reached the top layer of soil.

### Data source and integration

In this study, seven secondary datasets were integrated, which were obtained from the Government of India (GOI) and the Government of Tamil Nadu Institutional sources (Table 1). All data were subjected to the standardised quality control procedures, including the unit harmonisation, missing coordinate forward filling, excel serial date conversion and removal of duplicate data before analysis. The critical unit consistency issue EC in  $\mu\text{S}/\text{cm}$  for water quality datasets versus  $\text{dS}/\text{m}$  for soil datasets was resolved by maintaining  $\mu\text{S}/\text{cm}$  as the working unit for water data and applying the conversion factor  $1 \text{ dS}/\text{m} = 100 \mu\text{S}/\text{cm}$  only for direct comparisons. The spatial analysis was performed using QGIS Ver. 3.40 (“Bratislava”) and the shape file has been used from the USGS and the Survey of India.

The datasets differ in temporal coverage across datasets: groundwater quality (2015–23); soil (2023–26); rainfall (2013–23). The integrated cross-parameter conclusions were interpretive and directional rather than causal. Temporal mismatch, spatial sampling heterogeneity and institutional data collection protocols represent acknowledged limitations. All seven datasets were publicly available from the Government of India and the Government of Tamil Nadu portals. No individual data sharing agreements or formal access permission beyond standard academic use were required.

### Statistical and analytical methods

The data and statistical analysis were performed in the Python script using Python v3.13.13 and R Studio v4.5.2.

#### Rainfall variability

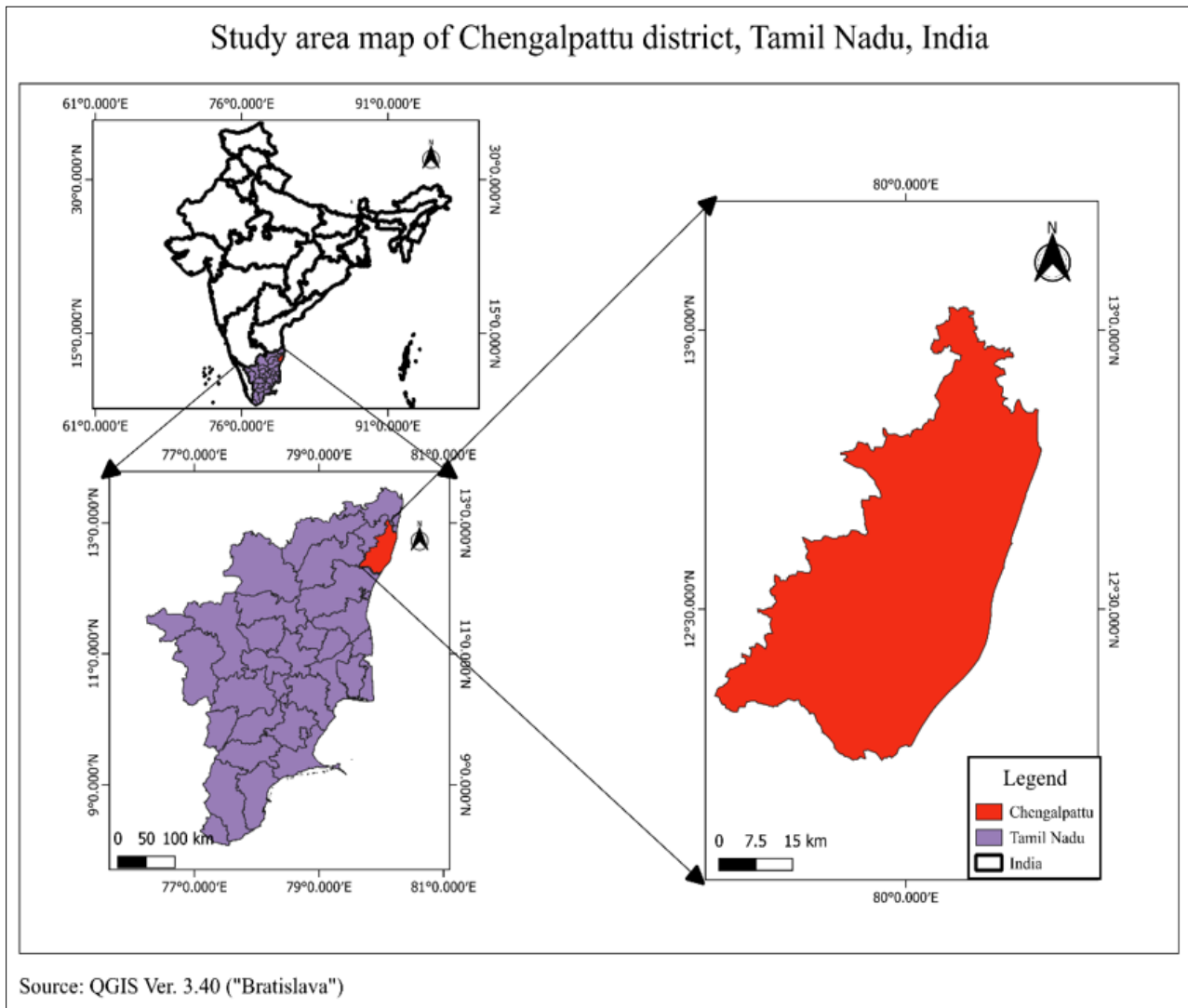
The long-term mean (LTM) annual rainfall was computed as the arithmetic mean of all valid annual totals from 2013–23. Annual percentage departure from the LTM was calculated as:

$$\text{Deviation (\%)} = \frac{(\text{Annual RF} - \text{LTM})}{\text{LTM}} \times 100 \quad (\text{Eq. 1})$$

**Table 1.** Summary of seven secondary datasets integrated in this

| Dataset                      | Source                                                                                                                                                       | Period    | No. of records | Key variables                      |
|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|----------------|------------------------------------|
| Daily rainfall (IMD Gridded) | India Meteorological Department                                                                                                                              | 2013–2023 | (approx.) 4020 | Daily RF (mm), season              |
| Groundwater quality          | TN SWand GW agency / CGWB                                                                                                                                    | 2015–2023 | 634            | EC, Cl, Na, SAR, pH, TDS           |
| Groundwater level            | CGWB routine monitoring                                                                                                                                      | 2013–2024 | 1523           | Water level (mbgl)                 |
| Soil test report             | Govt. Soil Testing Labs                                                                                                                                      | 2023–2026 | 4617           | EC (dS/m), pH, OC, N, P, K         |
| GEMS dug-well quality        | CGWB GEMS network                                                                                                                                            | 2013–2021 | 318            | EC, Cl, Na, NO <sub>3</sub> , F    |
| Rice crop statistics         | Directorate of Agriculture, TN and Block Level Agriculture Office and Seasonal Crop Report, Department of Economics and Statistics, Government of Tamil Nadu | 2013–2023 | 10 years       | Area (Ha), Prod. (T), Yield (T/Ha) |
| Surface water quality        | Central Water Commission                                                                                                                                     | 2015–2023 | 9 years        | EC, Cl, Na, pH, TDS, DO, BOD       |

RF: rainfall; EC: electrical conductivity; Cl: chloride; Na: sodium; SAR: sodium adsorption ratio; TDS: total dissolved solids; CGWB: Central Ground Water Board; DO: dissolved oxygen; BOD: biological oxygen demand; NO<sub>3</sub>: nitrate; TN: Tamil Nadu; GEMS: global environment monitoring system.



**Fig. 1.** Study area map.

Years were classified as deficit (departure < -20 %), normal if between -20 % to +20 % or excess (when departure > +20 %) following IMD classification. The CV ( $CV = \sigma/\mu \times 100$ ) was computed as a measure of inter-annual variability. Monotonic trends were tested using the Mann-Kendall (MK) non-parametric test and the Theil-Sen slope was estimated for trend magnitude (8,9).

#### Groundwater hydrochemical assessment

Descriptive statistics were performed for all major groundwater hydrochemical parameters (EC, chloride (Cl), sodium (Na), sodium adsorption ratio (SAR), pH, total dissolved solids (TDS)) across 634 station-year records. The EC values were classified following Central Ground Water Board (CGWB) thresholds: fresh (< 750  $\mu\text{S}/\text{cm}$ ), marginal (750–2250  $\mu\text{S}/\text{cm}$ ) and saline (> 2250  $\mu\text{S}/\text{cm}$ ). Chloride was classified per Bureau of Indian Standards/ Food and Agriculture Organisation (BIS/FAO) standards: safe (< 250 mg/L), marginal (250–500 mg/L), unsuitable (> 500 mg/L). The SAR was computed as:

$$SAR = \frac{Na^+}{\sqrt{[(Ca^{2+} + Mg^{2+})/2]}} \quad (\text{Eq.1})$$

where all ionic concentrations were calculated in milliequivalents per litre (meq/L) (10). Temporal trends in annual mean EC and Cl were independently tested using the MK test. The Pearson correlation coefficient was computed between paired annual rainfall and annual mean groundwater EC, no. of paired years ( $n$ ) = 9 (2015–23), which quantifies the rainfall-salinity

relationship.

Five Mann-Kendal tests were run on partially correlated hydrochemical and hydrological variables. To control the family-wise error rate at 0.05, the Bonferroni-corrected significance threshold was set at  $\alpha = 0.010$ . For missing data, annual means were calculated only for station-years with at least three valid readings. Years with fewer valid records were excluded from the time series instead of being imputed, to keep the non-parametric nature of the Man-Kendall test.

#### Water level trend analysis

Annual mean water table depth (mbgl) was computed from 1106 individual monitoring wells in Chengalpattu from 2013–24. Its change over this time were assessed using OLS linear regression and the MK test was applied to the annual mean time series to detect changes. A rising trend in mbgl indicated a declining water table, a worsening condition, while a decreasing mbgl indicated a shallower water table approaching the surface and increased salinisation risk.

#### Soil salinity characterisation

Soil EC has a main component to assess the soil salinity measured at 1 : 2 (soil: water) and was expressed in deciSiemens per metre (dS/m) from 4617 records collected across eight blocks, which were analysed. Block-level descriptive statistics, percentage frequency distributions by salinity class and soil organic carbon (OC) status were computed. Soil EC was classified by following

Tamil Nadu Agricultural University (TNAU)/BIS standards: Non-saline (< 0.2 dS/m), slightly saline (0.2–0.4 dS/m), moderately saline (0.4 – 0.8 dS/m) and highly saline (> 0.8 dS/m). These thresholds apply specifically to the 1 : 2 (soil : water) extract and were appropriate for this measurement method. The FAO/ United States Department of Agriculture (USDA) threshold of approximately 2 dS/m applied to the saturation extract (ECe), where  $ECe \approx 3 - 4 \times EC$  (1 : 2).

Soil pH was classified as neutral (6.5–7.5), alkaline (7.5–8.5) and strongly alkaline (> 8.5). Spatial inverse distance weighting (IDW) interpolation was performed in QGIS v3.40; leave-one-out cross-validation (LOOCV) yielded root mean square error (RMSE) = 0.04 dS/m for soil EC maps.

## Results and Discussion

### Rainfall variability (2013–23)

The annual rainfall at the study grid point (12.35° N, 79.86° E) exhibited marked inter-annual variability over eleven-year period (2013–23), with a long-term mean of 1161.2 mm and a CV of 49.5 %, which classified the district as rainfall with high variability among the agroecological zones of peninsular India and substantially exceeded the pan-India mean CV of approximately 25–30 % (Table 2, Fig. 2). Total annual rainfall ranged from a minimum of 480.7 mm in 2016 (–58.6 % departure) to a maximum of 2292.1 mm in 2021 (+97.4 % departure).

During the study period, five of the eleven years (2013, 2014, 2016, 2018, 2019) experienced deficit rainfall with annual departures below –20 %, while four years (2015, 2020, 2021, 2022) had exceeded the LTM. The MK test for monotonic trend in annual rainfall yielded  $\tau = +0.345$ ,  $Z = 1.40$ ,  $p = 0.161$ , indicating a non-significant increasing tendency. This finding was consistent with the broader pattern of episodic wet events intensifying

without a statistically confirmed long-term shift (Table 2).

Seasonal analysis further highlighted the dominant contribution of the Northeast (NE) Monsoon, which contributed a mean of 755.6 mm per annum across the study period compared with 333.7 mm from the Southwest (SW) Monsoon. The Northeast (NE) Monsoon was particularly influential in the two maximum-rainfall years. i.e., 2021 (1476.6 mm) NE and 2015 (1747.5 mm) NE. The rainfall anomalies observed in 2015 and 2021 were driven by cyclonic systems that made landfall along the Coromandel Coast and provided important natural experiments for assessing rainfall-driven dilution of groundwater saline load.

This extreme irregularity created high-frequency oscillation in the freshwater-saltwater equilibrium within the shallow aquifer system. The finding of no significant monotonic trend implied that the observed salinisation trends in other variables had reflected structural vulnerabilities such as falling water tables, shallow aquifer depth and coastal position rather than a simple monotonic drying of the climate.

### Groundwater hydrochemistry (2015–23)

Groundwater quality evaluation was carried out using the analysis of 634 station-years from the Tamil Nadu SW and GW Agency Monitoring Network. The data revealed that groundwater salinity in the Chengalpattu district has been characterised by marginal to moderate saline (EC values) (6, 11). Annual mean EC ranged from 870.1  $\mu\text{S}/\text{cm}$  in 2021 to 1204.4  $\mu\text{S}/\text{cm}$  in 2015, with an overall study-period mean of 1032  $\mu\text{S}/\text{cm}$ . The lowest EC coincided with the highest rainfall year (2021), providing clear evidence of rainfall-driven dilution of the shallow aquifer system, a pattern that was consistent with early findings for the Palar basin (6) and for southern Tamil Nadu (11).

Annual mean chloride concentration ranged from 120.8 mg/L (2023) to 216.4 mg/L (2019), with all annual averages remaining within the safe threshold (< 250 mg/L) under BIS classification. The SAR remained consistently low throughout the study period (range:

**Table 2.** Annual rainfall summary for Chengalpattu District (IMD grid point: 12.35° N, 79.86° E), 2013–23 (LTM = long-term mean, Class follows IMD deviation criteria)

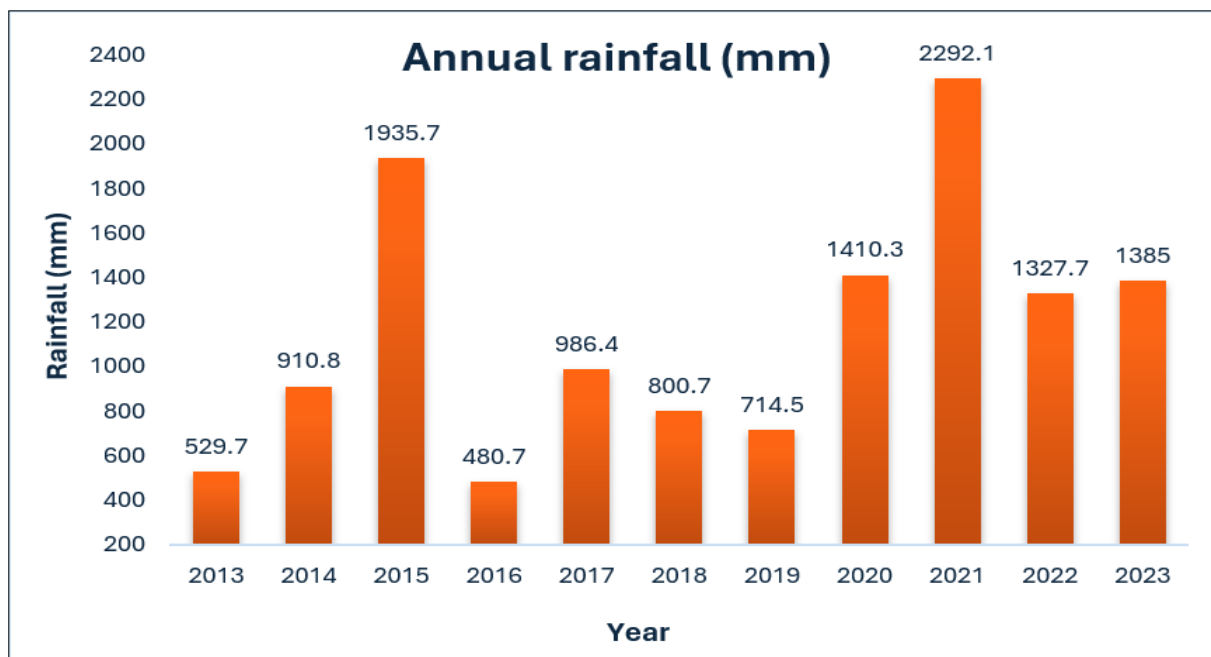
| Year | Annual RF (mm) | Departure (%) | Class   | SW Monsoon (mm) | NE Monsoon (mm) |
|------|----------------|---------------|---------|-----------------|-----------------|
| 2013 | 529.7          | –54.4         | Deficit | 279.7           | 234.7           |
| 2014 | 910.8          | –21.6         | Deficit | 406             | 401             |
| 2015 | 1935.7         | 66.7          | Excess  | 133.7           | 1747.5          |
| 2016 | 480.7          | –58.6         | Deficit | 221.1           | 158.4           |
| 2017 | 986.4          | –15.1         | Normal  | 368.9           | 603.7           |
| 2018 | 800.7          | –31.1         | Deficit | 187.2           | 591.4           |
| 2019 | 714.5          | –38.5         | Deficit | 136.6           | 577             |
| 2020 | 1410.3         | 21.5          | Excess  | 419.3           | 960.1           |
| 2021 | 2292.1         | 97.4          | Excess  | 598.7           | 1476.6          |
| 2022 | 1327.7         | 14.3          | Normal  | 335.2           | 833.9           |
| 2023 | 1385           | 19.3          | Normal  | 584             | 726.8           |
| LTM  | 1161.2         | Nil           | Nil     | 333.7           | 755.6           |

SW: southwest; NE: northeast; RF: rainfall.

**Table 3.** Annual mean groundwater hydrochemical parameters, Chengalpattu District

| Year | Mean EC ( $\mu\text{S}/\text{cm}$ ) | Mean Cl (mg/L) | Mean Na (mg/L) | Mean SAR | Mean pH | % Saline wells |
|------|-------------------------------------|----------------|----------------|----------|---------|----------------|
| 2015 | 1204                                | 188.7          | 124.2          | 3.09     | 7.96    | 4.6            |
| 2016 | 982                                 | 148.1          | 101.3          | 2.69     | 8.06    | 0              |
| 2017 | 1071                                | 179.7          | 106.5          | 2.69     | 7.95    | 2.7            |
| 2018 | 1028                                | 159.5          | 91.6           | 2.24     | 7.85    | 1.4            |
| 2019 | 1130                                | 216.4          | 99.7           | 2.34     | 7.86    | 1.4            |
| 2020 | 1147                                | 186.8          | 169            | 1.96     | 8.24    | 4.2            |
| 2021 | 870                                 | 131.2          | 74.4           | 2        | 8.13    | 0              |
| 2022 | 908                                 | 124.4          | 83.9           | 2.27     | 8.10    | 1.4            |
| 2023 | 945                                 | 120.8          | 94.4           | 2.56     | 7.68    | 0              |
| Mean | 1032                                | 161.7          | 105            | 2.43     | 7.98    | 1.7            |

TN SW and GW Agency, 2015–23; EC classification: marginal = 750–2250  $\mu\text{S}/\text{cm}$ ; SAR classification: low < 10 (USDA); percentage saline = wells with EC > 2250  $\mu\text{S}/\text{cm}$ . EC: electrical conductivity; Cl: chloride; Na: sodium; SAR: sodium adsorption ratio.



**Fig. 2.** Graphical representation of annual rainfall (mm) and period of 2013–23.

1.96–3.09), well below the USDA low SAR threshold of 10, indicating that sodium hazard to soils from irrigation had not yet reached at critical levels (Table 3).

The MK trend test for groundwater EC returned  $\tau = -0.333$ ,  $Z = -1.15$ ,  $p = 0.251$ , indicating no significant variation in trend over the 2015–23 window. The chloride trend approached marginal significance,  $\tau = -0.5$ ,  $Z = -1.77$ ,  $p = 0.076$ . At the Bonferroni-corrected threshold ( $\alpha = 0.010$ ), neither result was significant. These findings suggested that groundwater salinity had responded strongly to inter-annual rainfall variation, a dilution-concentration cycle rather than exhibiting a persistent directional deterioration detectable within the nine-year monitoring window.

With the number of years paired ( $n = 9$ ), the Pearson correlation between annual rainfall and annual mean groundwater EC was  $r = -0.14$  ( $p = 0.719$ ) and between rainfall and Cl concentration was  $r = -0.258$  ( $p = 0.503$ ). Although both coefficients showed a negative sign (higher rainfall to lower salinity), but neither achieved statistical significance given the limited sample size (critical  $|r| = 0.666$  at  $\alpha = 0.05$ ,  $df = 7$ ). A time series of at least 15 paired years would have been required to detect the observed correlation magnitude with adequate statistical power. The longer time series would have been necessary to test this relationship definitively.

Global environment monitoring system (GEMS) shallow

dug-well data ( $n = 318$ ) for the period of 2013–21 consistently showed higher EC values than the deeper borewell network, with annual mean EC ranging from 1240  $\mu\text{S}/\text{cm}$  (2020) to 1700  $\mu\text{S}/\text{cm}$  (2018), with a study period mean of 1521  $\mu\text{S}/\text{cm}$ . The mean was 47.4 % higher than the borewell network average. High-risk WQI classification averaged 40 % across monitoring years, peaking at 66.7 % in 2019. The concentration of nitrate in dug wells had a mean range of 25.5–57.4 mg/L, indicating co-contamination from agricultural nitrogen inputs in addition to saline intrusion.

This difference in EC between the dug and borewells confirmed that the shallow, unconfined aquifers had faced substantially greater salinisation pressure from lateral marine ingress. This observation was consistent with the Ghyben-Herzberg principle, whereby the freshwater-saltwater interface ascended as freshwater head diminished because of extraction or evapotranspiration.

#### Groundwater level trends (2013–24)

The annual mean water table depth at Chengalpattu monitoring wells exhibited the most statistically robust trend of all analysed variables. The mean water table depth declined, signifying that the water table had risen progressively closer to the ground surface from 6.9 mbgl (2013) to a minimum of 3.35 mbgl (2021), a net shallowing of 3.55 m over eight years at an OLS rate of -0.38 mbgl/year, where the  $R^2 = 0.82$ ,  $p < 0.0001$ . The MK test confirmed this monotonic trend

**Table 4.** Annual groundwater level statistics, Chengalpattu taluk (CGWB, 2013–24)

| Year | Mean WL (mbgl) | Min WL (mbgl) | Max WL (mbgl) | Std Dev | No. of Readings | Trend   |
|------|----------------|---------------|---------------|---------|-----------------|---------|
| 2013 | 6.9            | 1.5           | 29.8          | 5.88    | 48              | Stable  |
| 2014 | 6.97           | 1             | 25.66         | 4.66    | 65              | Stable  |
| 2015 | 6.48           | 0.5           | 13.4          | 3.04    | 85              | Stable  |
| 2016 | 6.32           | 1.22          | 16.3          | 3.18    | 115             | Stable  |
| 2017 | 6.54           | 0.5           | 16.3          | 3.9     | 104             | Stable  |
| 2018 | 5.94           | 1             | 15.7          | 2.83    | 112             | Falling |
| 2019 | 5.70           | 0.8           | 21            | 3.28    | 101             | Stable  |
| 2020 | 4.73           | 0.5           | 11.76         | 2.53    | 100             | Falling |
| 2021 | 3.35           | 0.1           | 10.03         | 2.33    | 123             | Falling |
| 2022 | 3.81           | 0             | 11.1          | 2.39    | 119             | Stable  |
| 2023 | 3.76           | 0.4           | 14.05         | 2.15    | 104             | Stable  |
| 2024 | 4.81           | 0.7           | 19.31         | 3.31    | 30              | Rising  |

WL: water table depth in metres below ground level (mbgl); Higher mbgl: deeper water table; MK trend:  $\tau = -0.818$ ;  $Z = -3.43$ ;  $p = 0.0006$ ; WL: water level.

with high confidence:  $\tau = -0.818$ ,  $Z = -3.43$ ,  $p = 0.0006$  (Table 4). The only variable that remained statistically significant after Bonferroni correction ( $\alpha = 0.010$ ). From 2021, a partial recovery became evident: the mean depth increased to 3.81 mbgl in 2022, 3.76 mbgl in 2023 and 4.81 mbgl in 2024. This partial recovery corresponded with the above LTM rainfall during 2021–23.

The shallowing water table had critical implications towards coastal salinisation. As the hydrostatic pressure of the freshwater head decreased, the Ghyben-Herzberg relationship predicts landward advancement of the freshwater-saltwater interface (12). A shallow water table also increased capillary rise and evaporative concentration of the dissolved salts in the vadose zone, which directly elevated the soil EC values. The minimum mean depth of 3.35 mbgl recorded in 2021 had been interpreted in the context of concurrent extreme rainfall (2292 mm) under drought conditions; this depth would likely have been shallower, further amplifying the intrusion risk. This finding was consistent with early results for East Indian coastal alluvial aquifers (4) and on seawater intrusion vulnerability along India's East Coast (3).

### Dynamics of surface water quality (2015–23)

Annual records obtained from the Central Water Commission monitoring station on the east-flowing river in Chengalpattu district revealed a statistically increasing trend in EC: MK  $\tau = 0.611$ ,  $Z = 2.19$ ,  $p = 0.029$ ; OLS slope =  $67.5 \mu\text{S/cm/yr}$ ,  $p = 0.013$ . This trend had also passed the Bonferroni corrected threshold ( $\alpha = 0.010$ ) and represented the second confirmed significant result in this study.

In practical terms, the surface water EC was increased from 212  $\mu\text{S/cm}$  in 2015 (fresh water) and it increased to a peak of 1013.3  $\mu\text{S/cm}$  in 2022 (marginal class), representing a nearly five-fold increase over 7 years.

The concentration of chloride also exhibited a notable increase in trend from 28.9 mg/L in the year of 2015 to 185.7 mg/L in the year of 2022, followed by a partial recovery to 158.7 mg/L in the year of 2023. Despite the limited dataset with an annual record count ( $n = 9$ ), these results served as supplementary evidence. The notable MK trend highlights a significant salinisation signal which impacts the Chengalpattu's water resources across the various compartments like groundwater, surface water and soil.

### Soil salinity characterisation (8 Blocks, 4617 records)

Soil test data from 4617 samples across the eight administrative blocks of Chengalpattu district from 2023–26 provided a spatially distributed characterisation of current soil salinity status (Table 5). Across the full district dataset, the mean soil EC was 0.206 dS/m and the SD = 0.306 dS/m, with a pH mean of 7.61 and the SD = 0.39. The salinity class distribution was,

- ◆ Non-saline (<0.2 dS/m) - 59.9 % of samples.
- ◆ Slightly saline (0.2–0.4 dS/m) - 32.6 %
- ◆ Moderately saline (0.4–0.8 dS/m) - 6.2 %
- ◆ Highly saline (> 0.8 dS/m) - 1.3 %.

The overall analysis indicated that most of the cultivated soils remained non-saline to slightly saline. However, 7.5 % in the moderate-to-high salinity classes represented a significant area that requires immediate management, given the district's total agricultural extent.

All the blocks were observed for spatial heterogeneity, with the Madhuranthagam block showing more area under moderately saline soils 20 % and highly saline soils 5.2 %. It also had the mean EC value of 0.332 dS/m, the highest mean at block level and particularly the highest mean organic carbon at 1.796 % (Table 5). The elevated organic carbon in Madhuranthagam may have reflected the ameliorative effect of organic matter on soil structure, but the high salinity percentage indicates ongoing accumulation of salt that had been linked to its low-lying riparian position. Lathur block had 8.4 % of area that was moderately saline and 1.7 % highly saline soils and also recorded the lowest average organic carbon of all blocks is 0.318 % a combination that suggests reduced soil buffering capacity against salt stress. In Kattankolathur and Thirukalakundram blocks, recorded low mean EC values; these blocks also recorded extreme maximum EC outliers of 16 and 7.09 dS/m, respectively, indicating the presence of localised, highly saline microsites that require field investigation (Fig. 3–11).

The correlation between soil salinisation hotspots and low organic carbon has ecologically relevant: organic matter improves aggregate stability, water retention and cation exchange capacity. All of which buffered against salt stress (2). The low mean OC values across most blocks (0.30–0.50 %), well below the 1.00 % threshold recommended by TNAU for productive rice soils, indicate that the soil system lacks the organic matter capital necessary to buffer salinity impacts. Lathur block, with the lowest OC (0.30 %) combined with the highest block-level moderate salinity incidence, represented the most immediate management priority. Targeted green manuring, compost application and salt-tolerant variety deployment should be considered for this block.

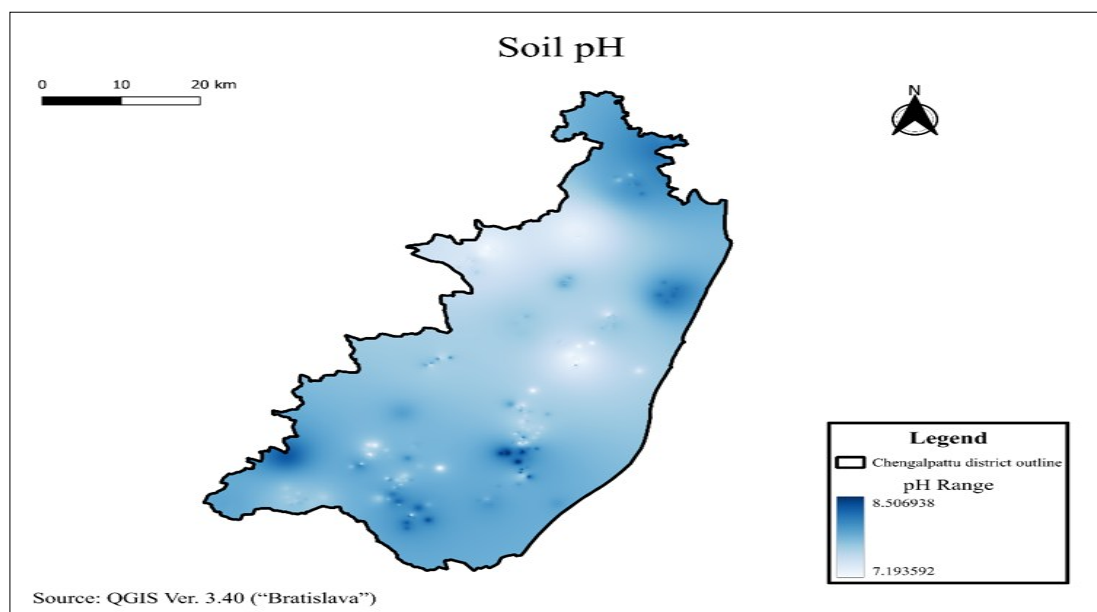
### Rice cultivated area and yield trajectory (2013–23)

Rice was the dominant crop in the Chengalpattu district. It was cultivated across three seasons, viz., kharif, autumn and winter. On observing (2013–23), the time series of the total cultivated area alongside yield variability is consistent with mounting

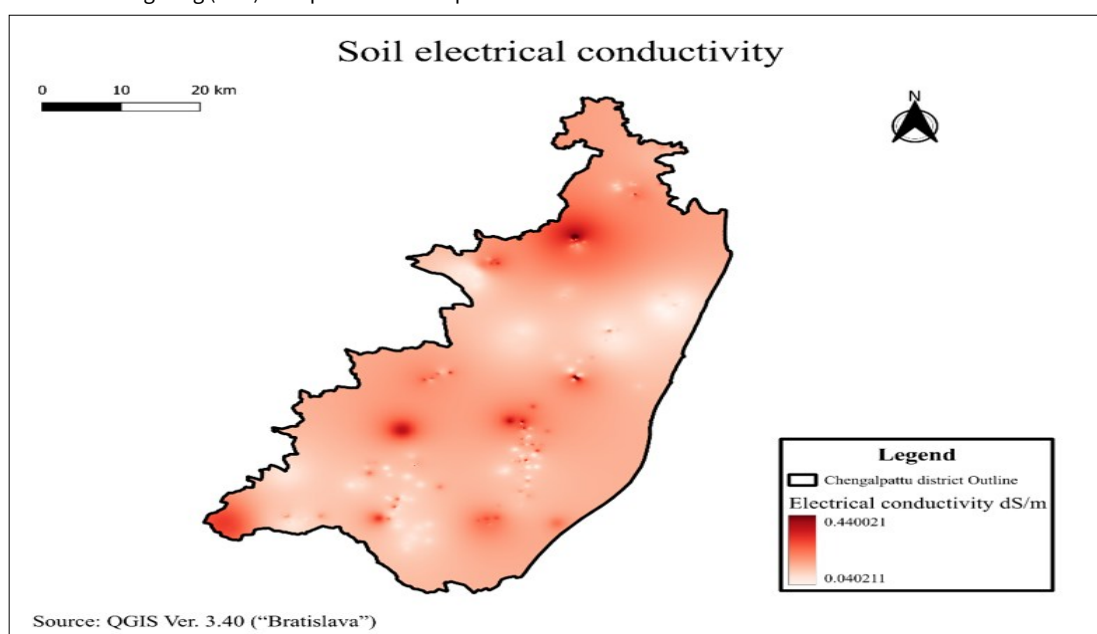
**Table 5.** Block-level soil salinity summary, Chengalpattu District

| Block            | No. of records | Mean pH | EC Mean (dS/m) | EC Max (dS/m) | Mean OC (%) | Mod. saline (%) | High saline (%) |
|------------------|----------------|---------|----------------|---------------|-------------|-----------------|-----------------|
| Acharapakkam     | 616            | 7.62    | 0.183          | 0.78          | 0.4         | 3.4             | 0               |
| Chithamoor       | 611            | 7.69    | 0.168          | 1.46          | 0.46        | 2.3             | 0.5             |
| Kattankolathur   | 703            | 7.33    | 0.190          | 16*           | 0.48        | 1.7             | 0.7             |
| Lathur           | 406            | 7.70    | 0.216          | 1.77          | 0.32        | 8.4             | 1.7             |
| Madhuranthagam   | 674            | 7.70    | 0.332          | 1.95          | 1.8         | 20              | 5.2             |
| St Thomas Mount  | 536            | 7.85    | 0.211          | 0.68          | 0.31        | 7.8             | 0               |
| Thiruporur       | 709            | 7.59    | 0.173          | 1.52          | 0.79        | 3.2             | 1.4             |
| Thirukalakundram | 362            | 7.48    | 0.149          | 7.09*         | 0.43        | 1.9             | 0.6             |
| District Mean    | 4617           | 7.61    | 0.206          | 16            | 0.67        | 6.2             | 1.3             |

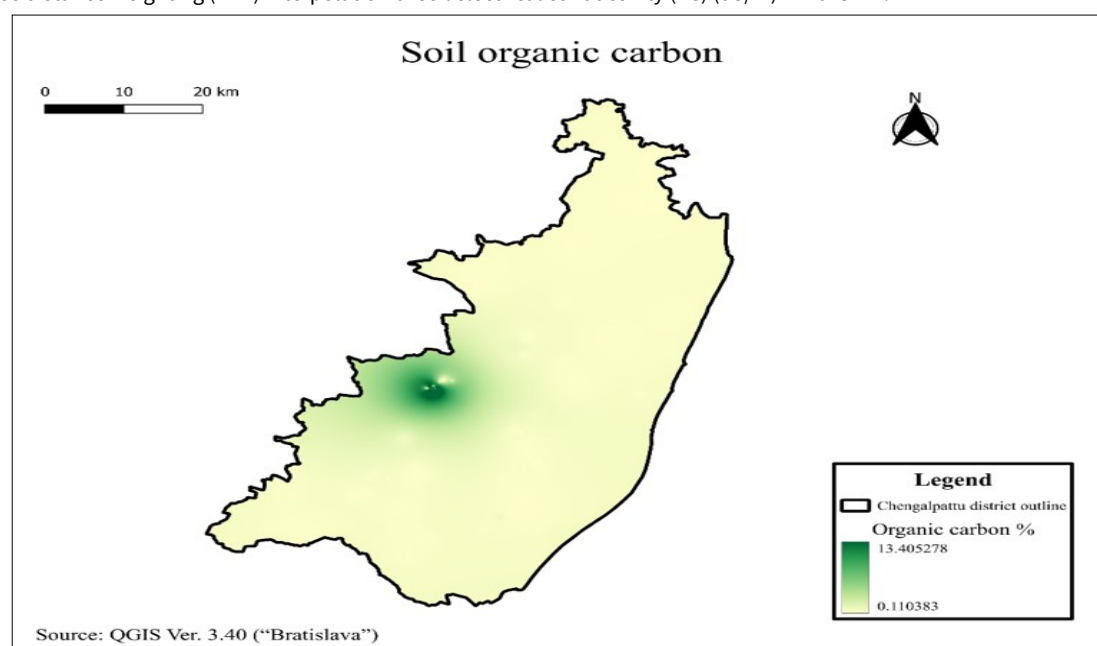
Government Soil Testing Laboratory,  $n = 4617$ ; \*Extreme outliers likely reflecting localised saline microsites; EC in dS/m (1 : 2 extract); OC = organic carbon percentage; Mod. saline = 0.4–0.8 dS/m; high saline > 0.8 dS/m; EC: electrical conductivity.



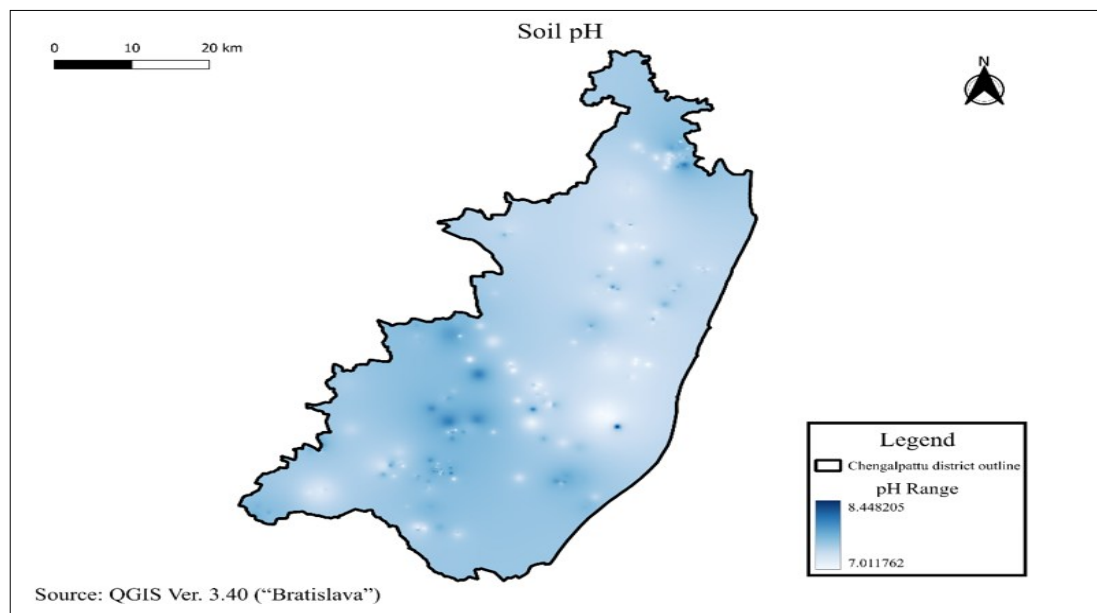
**Fig. 3.** Inverse distance weighting (IDW) interpolation of soil pH in 2023–24.



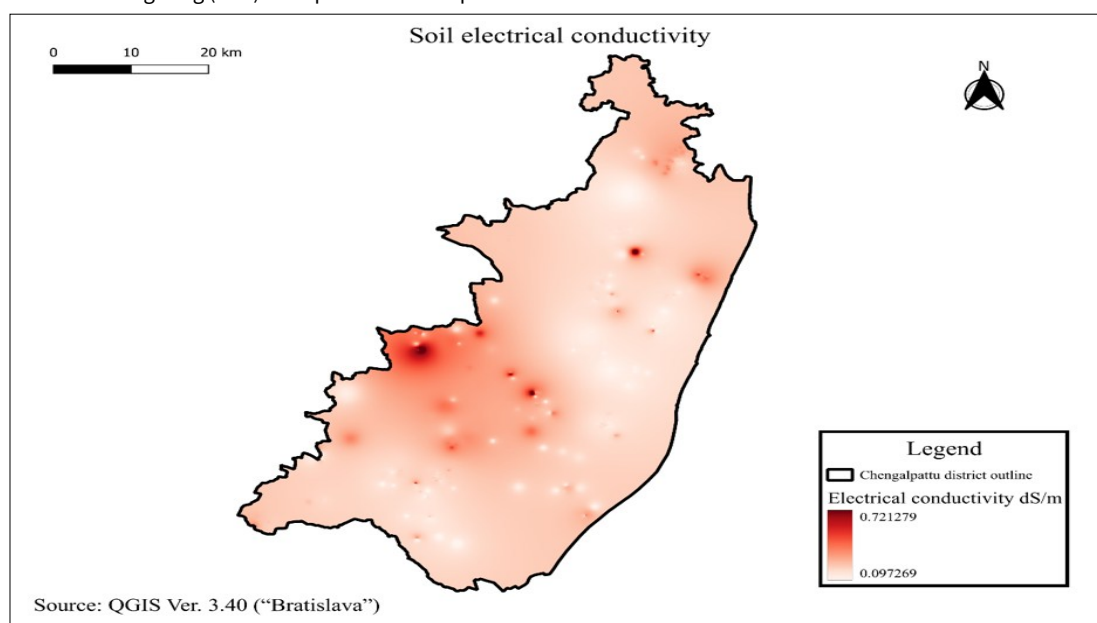
**Fig. 4.** Inverse distance weighting (IDW) interpolation of soil electrical conductivity (EC) (dS/m) in 2023–24.



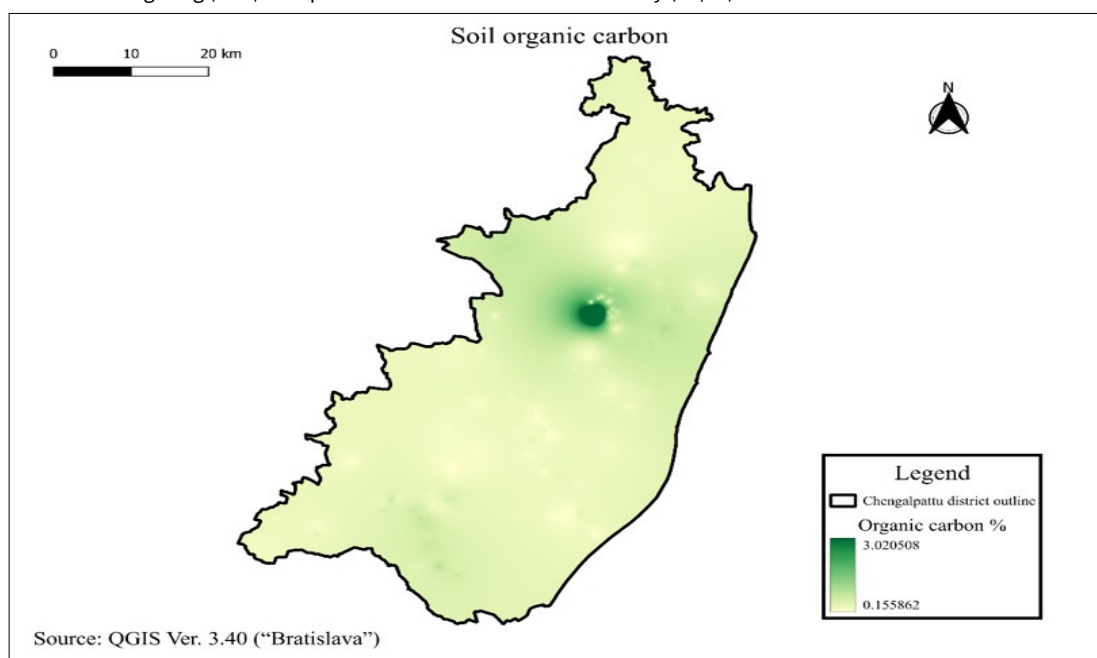
**Fig. 5.** Inverse distance weighting (IDW) interpolation of soil organic carbon (%) in 2023–24.



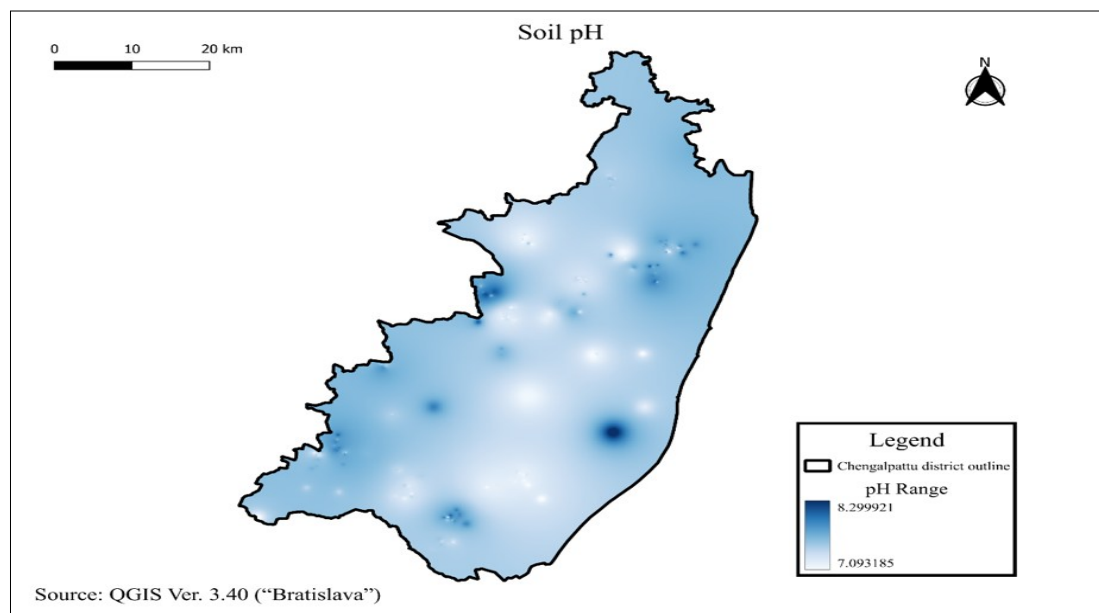
**Fig. 6.** Inverse distance weighting (IDW) interpolation of soil pH in 2024–25.



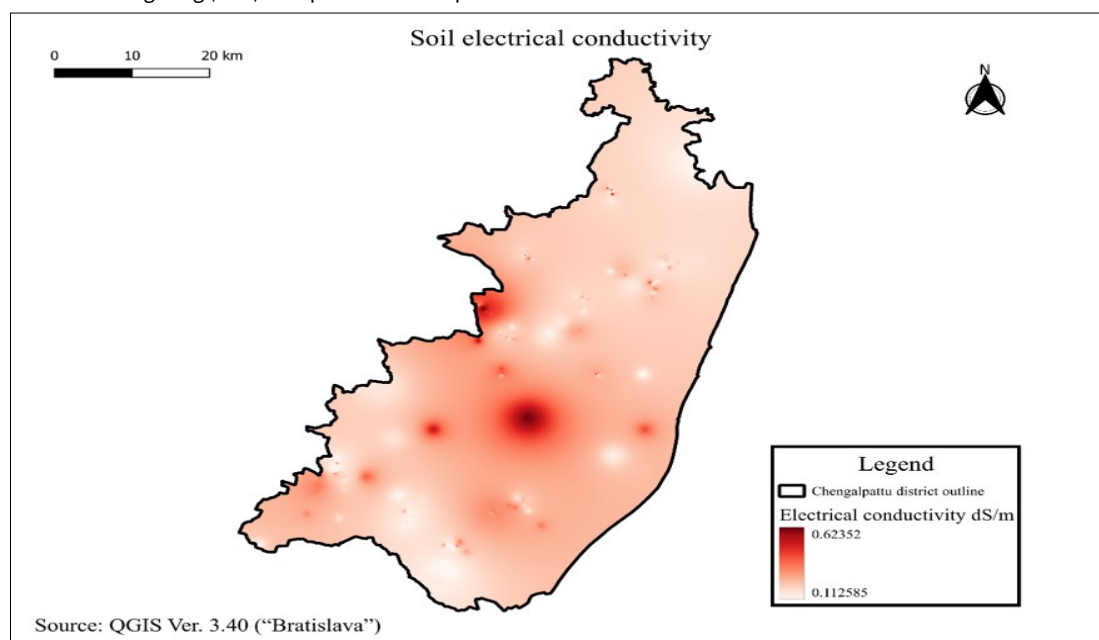
**Fig. 7.** Inverse distance weighting (IDW) interpolation of soil electrical conductivity (dS/m) in 2024–25.



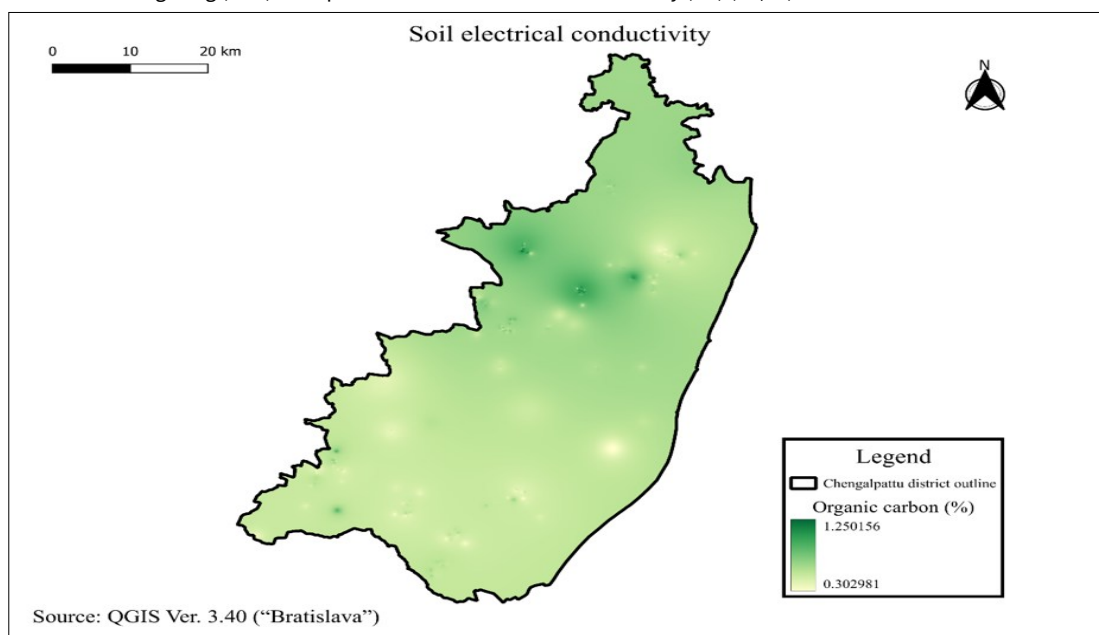
**Fig. 8.** Inverse distance weighting (IDW) interpolation of soil organic carbon (%) in 2024–25.



**Fig. 9.** Inverse distance weighting (IDW) interpolation of soil pH in 2025–26.



**Fig. 10.** Inverse distance weighting (IDW) interpolation of soil electrical conductivity (EC) (dS/m) in 2025–26.



**Fig. 11.** Inverse distance weighting (IDW) interpolation of soil organic carbon (%) in 2025–26.

abiotic stress. Total rice cultivated area peaked at 97738 ha in 2015–16 and contracted to 40691 ha in 2019–20, showing a decline of 58.3 % yield in four years.

Between 2020–23, around 49000–50000 ha of area were stabilised and partial recovery was observed. Over the past decade, the mean total area was 62912 ha. The OLS regression analysis of total area against time produced a significant negative slope (MK:  $\tau = -0.600$ ,  $p = 0.020$ ), consistent with a progressive trend of area contraction.

Yield per hectare (t/ha) exhibited significant variability and lacked a consistent monotonic trend (MK:  $\tau = -0.378$ ,  $p = 0.152$ ). During the year 2021–22 the lowest yield was recorded at 3.55 t/ha and from the year 2022–23, 3.75 t/ha were recorded, despite the high rainfall during those years. This pattern may indicate that waterlogging stress and standing water damage have been more significant than drought or salinity in those seasons. During the period of 2019–20, the peak yield recorded was 4.97 t/ha, characterised by the moderate rainfall and the absence of extreme weather conditions. The simultaneous decline in cultivated area alongside yield variability is consistent with a scenario where saline-susceptible soils are increasingly left fallow while farming continues in higher-quality inland soils, thus partially obscuring yield losses in the overall statistics. However, attributing this decline solely to salinisation would have been an oversimplification. Urbanisation and land-use conversion in peri-urban blocks (St Thomas Mount, Thiruporur), driven by industrial and IT corridor expansion, market dynamics favouring horticultural crops and agrarian distress reducing farm labour availability also play significant roles. Without a multivariate econometric model disentangling these drivers, the rice area decline cannot be exclusively attributed to salinity; the spatial correlation of area reduction, moderate soil salinity and deteriorating groundwater quality in coastal blocks indicates that salinity is a plausible contributing factor that may increasingly become dominant.

### Synthesis and integrated risk framework

Synthesising across all seven datasets, this study identified three crucial converging risk factors that defined Chengalpattu's salinisation trajectory: (i) extreme inter-annual rainfall variability, (CV = 49.5 %) which had created oscillating recharge-stress cycles; (ii) a rapidly shallowing water table ( $-0.38$  mbgl/yr,  $p < 0.0001$ ) which had amplified capillary saline uplift and reduced the hydraulic barrier to marine intrusion; and (iii) a surface water quality trajectory that had already crossed the fresh/marginal boundary at the CWC monitoring station (EC = 212 to 1013  $\mu\text{S}/\text{cm}$ , MK  $p = 0.029$ ).

These three factors were analysed at different temporal scales: seasonal, annual-decadal and interannual, respectively, but they reinforced each other through shared geophysical processes. The data from the GEMS dug-well introduced a fourth dimension to the assessment indicating that the shallow aquifer had already become substantially more saline with the average of 1521  $\mu\text{S}/\text{cm}$  than the deeper borewell network and showed a 40 % average high-risk water quality index (WQI) rate, suggesting that the deterioration visible in surface water quality and water table trends had already manifested in the shallow subsurface. The soil data provided the terminal expression of these stressors: approximately 7.5 % of the agricultural area was moderately to

highly saline, with spatially clustered risk concentrated in Madhuranthagam and Lathur blocks.

### Conclusion

This study provided a comprehensive multi-dataset assessment of climate-induced soil salinisation and saltwater intrusion in coastal areas of Chengalpattu district from 2013–24. The principal findings are: (i) annual rainfall exhibits extreme inter-annual variability (CV = 49.5 %) with five deficit years over 2013–23, but no statistically significant directional trend (MK:  $p = 0.350$ ); (ii) groundwater EC averaged 1032  $\mu\text{S}/\text{cm}$  (marginal class) across 634 station-year records with no significant trend, though fluctuations inversely tracked rainfall; (iii) the groundwater table demonstrated a highly significant shallowing trend (MK:  $\tau = -0.697$ ,  $Z = -3.09$ ,  $p = 0.002$ ; OLS:  $-0.258$  mbgl/year), representing a 3.55 m net rise between 2013 and 2021; (iv) surface water EC increased significantly (MK:  $\tau = 0.611$ ,  $p = 0.029$ ; OLS slope = 67.5  $\mu\text{S}/\text{cm}/\text{year}$ ); (v) 7.5 % of 4617 soil samples were moderately to highly saline, with Madhuranthagam (25 % moderate-high) and Lathur (10 %) as priority intervention blocks; and (vi) rice cultivated area contracted by 58.37 % from 2015–16 to 2019–20.

These findings indicated that Chengalpattu district was currently in an intermediate stage of salinisation where critical thresholds had not yet been exceeded, but underlying hydro-climatic and soil processes had been actively progressing toward greater risk. This stage represented a critical period for preventive intervention.

Policy recommendations included: (i) block-level groundwater regulation with mandatory water table monitoring in Madhuranthagam, Lathur and Kattankolathur blocks; (ii) organic matter restoration programmes to build soil buffering capacity, targeting the 0.75 % OC threshold; (iii) promotion of salt-tolerant rice varieties (e.g., CSR-36, CST-7-1) and alternative crops in saline-prone blocks; (iv) restoration of wetland and mangrove buffers along coastal margins to reduce saltwater intrusion velocity and (v) establishment of a real-time, multi-parameter groundwater and soil monitoring network to enable early warning of threshold exceedances. Future research should incorporate extended groundwater monitoring records ( $\geq 15$  years), multivariate econometric analysis to disentangle drivers of cropland decline and satellite-based normalised difference vegetation index (NDVI) and soil moisture time series for spatial upscaling.

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## Authors' contributions

SSP carried out the drafted manuscript and QGIS map image generation. TSRR and RAS carried out the soil studies and soil parameters. KSK carried out the statistical work. TT carried out the data analysis and code correction. All authors have read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Quill Bot and AI-ChatGPT to paraphrase and correct grammatical errors in document writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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