

Assessment of Hydrochemical Controls and Water-Use Suitability of Surface Waters in The Gadilam River Basin, Tamil Nadu, India

Mrs.E.Nivetha¹, Dr.R.Mathiyazhagan²

¹Research Scholar, Department of Civil Engineering, FEAT, Annamalai University.

²Professor, Department of Civil Engineering, FEAT, Annamalai University.

Abstract

Coastal river basins are influenced by multiple interacting factors while most index-based assessments focus on groundwater and evaluate a single water use based suitability analysis. This study involved thirty-eight surface water samples collected from estuaries backwaters tanks and the Gadilam River within the Gadilam River Basin. Eighteen water quality parameters were measured and separate indices computed for drinking, domestic and irrigation use, with entropy-derived weights verifying the drinking classification. Composition is dominated by a longitudinal salinity gradient. Electrical conductivity ranges from 284 to 8,788 $\mu\text{S}/\text{cm}$, the sodium to chloride ratio converges on the seawater value of 0.858, and chloride-based mixing fractions reach 15% downstream. Two additional controls act independently with nutrient enrichment indicated by the strong correlation between nitrate and phosphate ($r = 0.942$) and higher concentrations upstream of the tidal limit while redox mobilization of iron and manganese is strongly correlated ($r = 0.828$) and unrelated to salinity. The drinking water quality index spans 28.8 to 466.1, averaging 42.4, 73.8 and 241.9 in the upper, middle and lower reaches, and classifies 17 samples Excellent, eight Good, seven Poor, one Very poor and five Unsuitable. Twenty samples comply with the Indian drinking water specification while 18 do not with iron being the largest contributor to poor drinking water quality in 20 samples. Fifteen of the 21 lakes rated Excellent for drinking are classified as Good for domestic use while six sources classified as non-potable due to iron remain suitable for irrigation.

Keywords: Surface water quality; Water Quality Index; Domestic water usage; irrigation suitability; entropy weighting; Gadilam river basin.

1. INTRODUCTION

Water scarcity is now as much a problem of quality as of quantity. Pollutant loading reduces the share of the resource that can be abstracted for a given purpose and so compounds physical shortage and slows progress towards the water and sanitation targets of Sustainable Development Goal 6 (Paramanik, 2026). Surface water bodies receive this loading first. They integrate the geology they drain, the land use around them and the effluent discharged into them, and their shallow and exposed condition allows them to respond within weeks rather than decades. Their chemistry is therefore an early and sensitive record of catchment stress and its periodic assessment is a prerequisite for allocating water between competing uses.

Seasonality sharpens the problem in India. Most peninsular basins receive the bulk of their rainfall within a few monsoon months. River channels, irrigation tanks and small lakes then sustain domestic abstraction and command area irrigation for the remainder of the year. Dilution capacity falls as the dry season advances so that an unchanged pollutant load yields progressively higher concentrations. Recent assessments of Indian rivers report a consistent decline in quality and show that the decline is spatially uneven within a single basin (Yash et al., 2024; Rahi et al., 2025). Surface water in these settings is often used directly and with little or no treatment, so the chemical state of an individual water body translates at once into exposure for the population dependent on it.

Coastal basins are subject to a further control. Their lower reaches lie near the tidal limit where mixing with seawater raises chloride, sodium and total dissolved solids well above the concentrations that catchment processes alone can generate. The resulting longitudinal salinity gradient can be steep enough to render water unsuitable for drinking and for irrigation over a short distance. Investigations along the Tamil Nadu coast have documented this process and report a widening affected zone in several districts (Vijayakumar et al., 2024; Mophin Kani et al., 2026). The consequence for agriculture is direct, since elevated electrical conductivity depresses crop water uptake while a high proportion of sodium relative to calcium and magnesium degrades soil structure and reduces infiltration (Richards, 1954; Ayers and Westcot, 1985). Assessment in such a basin must therefore resolve position along the gradient rather than report a single basin-wide summary.

Salinity is rarely the only control in operation. Nutrient enrichment acts independently of it under the influence of fertiliser application and domestic wastewater and may be amplified in impounded water bodies where long residence times limit flushing (Giblin et al., 2026). Estuarine and near-coastal waters receiving such loads can show nutrient distributions governed by the pattern of discharge rather than by salinity (Xiao et al., 2025), and the health significance of the nitrate component is well established (Verma et al., 2023). Iron and manganese

represent a third and separate consideration. Both are mobilised under reducing conditions in sediments and waterlogged soils, so their distribution need not follow either salinity or nutrient supply, and they govern acceptability at low concentrations through taste, colour and staining while manganese additionally carries a health-based provisional guideline value (BIS, 2012; WHO, 2022; Belyanovskaya et al., 2025). A basin may therefore be constrained by more than one mechanism at the same time, and an assessment that resolves only one of them will understate the problem.

Water quality indices compress such multivariate information into a single interpretable value. The weighted arithmetic formulation of Brown et al. (1972) remains the most widely applied and has been used extensively in Indian basins to rank sampling locations and delineate zones of impairment (Vasanthavigar et al., 2010; Promilton et al., 2025). Its principal weakness is the subjectivity of the weights, because two investigators weighting the same parameter set may reach different classifications from identical data. Entropy weighting addresses this by deriving weights from the dispersion of the measurements themselves, and comparison of the two schemes has become a standard test of index stability (Gautam et al., 2022; Ukoha-Onuoha, 2026). Irrigation suitability requires separate treatment because the parameters limiting crop production are not those limiting potability. The index of Meireles et al. (2010) is built on electrical conductivity, sodium, bicarbonate, chloride and the sodium adsorption ratio and is commonly reported alongside the classical criteria of Wilcox (1955) and Eaton (1950) and the salinity and sodium hazard diagram of Richards (1954) (Ghosh and Bera, 2023; Vyas et al., 2024). Domestic use lies between the two and is governed principally by hardness and by the scaling and corrosion tendency expressed through saturation indices (Langelier, 1936; Ryznar, 1944).

Four gaps persist in this literature. Most index-based assessments in coastal India address groundwater while the surface water bodies meeting domestic and irrigation demand in the same catchments receive far less attention, despite responding faster to contamination. Most studies also evaluate a single use, so that drinking, domestic and irrigation suitability are reported interchangeably or one is inferred from another even though their limiting parameters differ. The conventions underlying the calculation are frequently left unstated, including the basis of the weights, the ideal value assumed for each parameter and the treatment of concentrations outside the rating range, which makes published values difficult to compare and allows weight concentrated on a single trace parameter to dominate the result. Finally, the controls on composition are seldom separated from one another, although the distinction determines where any management response should be directed.

The Gadilam river basin in Cuddalore district, Tamil Nadu, provides a setting in which these gaps can be addressed. It crosses three contrasting geological domains between its hard rock headwaters and its tidal outlet, supports lignite mining and a large industrial estate alongside intensive irrigated agriculture, and its lower reach lies within the zone of marine influence. The hydrogeochemistry of the basin has been characterised through major ion chemistry, multivariate statistics and stable isotopes, but that work addressed groundwater and the evolution of the aquifer system across the hard rock and sedimentary contact (Prasanna et al., 2009, 2010, 2011). No comparable index-based assessment exists for the surface water bodies of the basin, and the suitability of its river reaches, irrigation tanks, lakes and backwaters for drinking, domestic and agricultural use has not been established on a common basis.

Thirty-eight surface water samples comprising twenty-one lakes and irrigation tanks, thirteen river locations, two estuarine stations and two backwater stations were therefore collected across the basin in January 2026 and analysed for eighteen physical and chemical parameters. The objectives were fourfold: to characterise the spatial variability of the physicochemical parameters and the major and minor ions across the basin; to assess suitability for drinking, domestic and irrigation use through established water quality indices, reporting both the expert and the entropy weighting schemes for the drinking index and both tail conventions for the irrigation index; to examine the relationships among the measured parameters through correlation analysis and to identify the dominant controls on composition; and to integrate the hydrochemical and index results in order to identify the critical water quality concerns of the basin and the monitoring and management responses they imply.

2. MATERIALS AND METHODS

2.1 Study area

The Gadilam river basin occupies approximately 1,628 km² of the Cuddalore, Kallakurichi and Villupuram districts of Tamil Nadu, southern India, between latitudes 11°30' and 11°55' N and longitudes 79°00' and 79°47' E (Figure 1). The river rises in the hard rock terrain of the western uplands near Kallakurichi, flows east-northeast across a sedimentary tract and discharges into the Bay of Bengal immediately north of Cuddalore town, the main channel extending some 85 km. Relief is subdued, the digital elevation model indicating a maximum of 171 m above mean sea level in the western headwaters and -7 m in the coastal tract, so that the longitudinal gradient over the lower

half of the basin is less than 2 m per kilometre. This gentle gradient offers little hydraulic resistance to tidal propagation and permits marine water to penetrate a considerable distance inland. Drainage is parallel to sub-parallel throughout (Prasanna et al., 2010). The basin is underlain by three principal stratigraphic units arranged in sequence from west to east. The Archaean crystalline complex, comprising charnockite, granite, syenite, garnetiferous gneiss, leptinite and schist, forms the upstream catchment. Cretaceous limestone and the Tertiary Cuddalore Sandstone Formation occupy the midstream tract, and Recent alluvium underlies the downstream and coastal reaches. A faulted contact separates the hard rock terrain of the west from the sedimentary formations of the east (Prasanna et al., 2010, 2011). This lithological transition is relevant to the present study in two respects: it governs the weathering-derived solute load acquired in the upper basin, and the permeable alluvial and sandstone formations of the lower basin provide the pathway along which marine water interacts with the river in its tidal reach. The climate is tropical sub-humid. Mean annual rainfall is approximately 1,643 mm, the greater part of which is delivered by the northeast monsoon between October and December, with a secondary contribution from the southwest monsoon between June and September (Prasanna et al., 2010). The basin supports intensive agriculture, principally paddy cultivation under tank and canal irrigation in the upper and middle reaches. Lignite mining by the Neyveli Lignite Corporation and the SIPCOT industrial estate situated near the coast at Cuddalore constitute the principal industrial activities within the catchment (Prasanna et al., 2009)

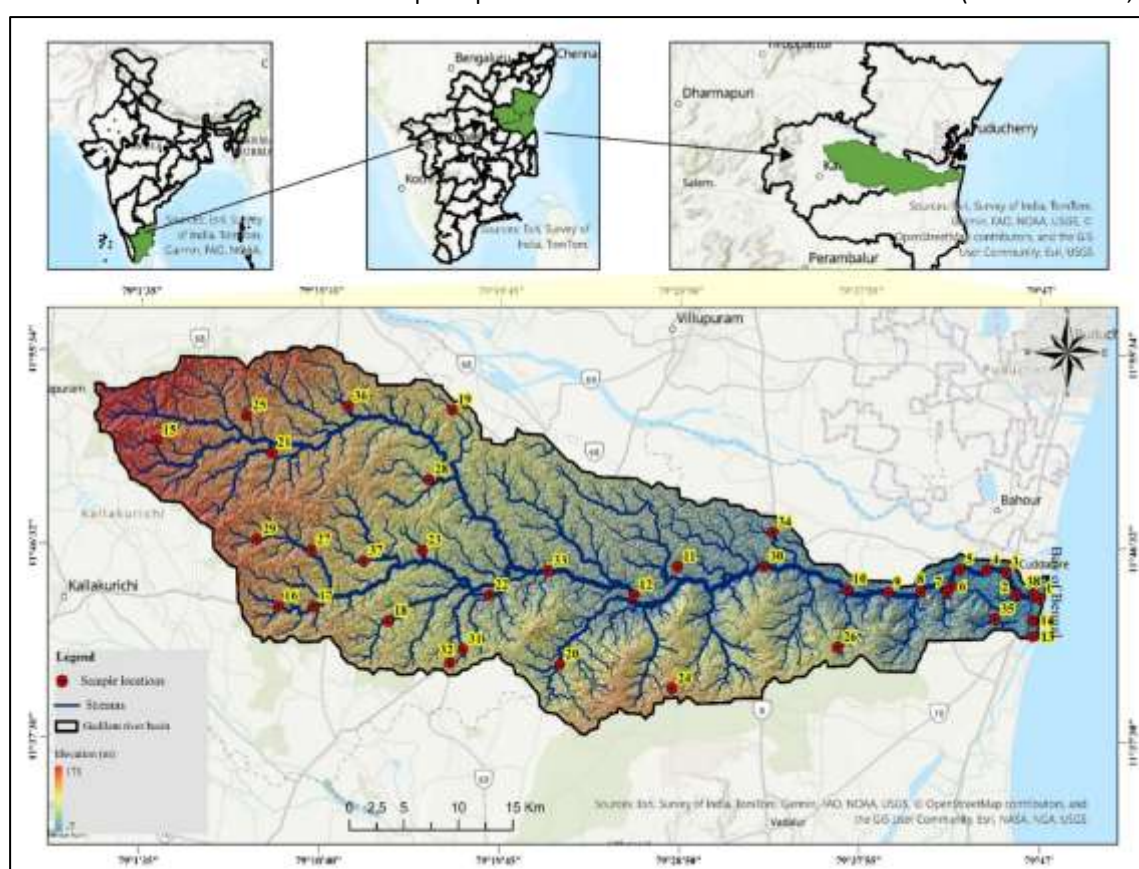


Fig. 1. Location of the Gadilam river basin in Cuddalore and Villupuram districts, Tamil Nadu, with insets showing its position within India and within the state. The main map presents the drainage network; elevation derived from a digital elevation model and the 38 surface water sampling points.

2.2 Sample collection and field measurement

Thirty-eight surface water samples were collected across the basin during January 2026, immediately following the northeast monsoon. Sampling points were distributed along the trunk channel and its principal tributaries from the headwaters to the river mouth, and were selected to represent the full range of surface water bodies upon which the basin depends: 21 samples were drawn from tanks and irrigation reservoirs, 13 from the river channel, two from the estuary and two from the associated backwater bodies. No groundwater samples were included. Sampling locations are shown in Figure 1. The network was designed to resolve change along the

longitudinal axis rather than to achieve uniform areal coverage, since the controlling gradient in a coastal basin is the distance from the tidal limit. Station spacing was accordingly closer in the lower reach, where composition changes most rapidly, than in the headwaters. For the presentation and interpretation of results the basin is divided into three reaches on the basis of position along the channel: an upper reach west of approximately 79°22' E comprising 18 samples, a middle reach between 79°22' and 79°38' E comprising seven samples, and a lower reach east of 79°38' E comprising 13 samples, the last encompassing the estuary, the backwater bodies and the tidal section of the river. Collecting the entire network within a single month removes seasonal variation as a confounding influence, so that the differences reported between stations may be attributed to position and to local inputs rather than to the date of sampling.

Sample collection followed the procedures set out in Section 1060 of APHA (2023), the corresponding Indian Standard methods of the IS 3025 series being equivalent. Narrow-mouth high-density polyethylene bottles of one litre capacity were used throughout, polyethylene being preferred to glass because it does not release silica or sodium into weakly mineralised water on standing. Each bottle was washed in detergent, steeped in dilute hydrochloric acid, rinsed repeatedly in deionised water and dried before being taken into the field, and was then rinsed three times with the water about to be sampled immediately before filling. At each station the sample was drawn from approximately 0.3 m below the surface at a point clear of the bank and away from any visible local disturbance such as a cattle crossing, a washing place or a drain outfall. The bottle was uncapped beneath the surface and filled without headspace, which limits exchange with the atmosphere and the consequent loss of dissolved carbon dioxide that would otherwise raise the measured pH. At the estuarine and backwater stations, where vertical stratification in salinity may develop under tidal influence, the same sampling depth was maintained so that comparability across the network was preserved. The coordinates of every station were recorded in the field with a handheld satellite navigation receiver referred to the WGS 84 datum and were subsequently checked against the drainage network and against imagery before the maps were prepared. Temperature, TDS, pH and electrical conductivity alter during storage and were therefore determined in the field at the moment of collection using a Hanna Instruments HI98594 portable logging multiparameter system fitted with an HI7698594 multisensor probe.

2.3 Analytical procedures

Eighteen Parameter were measured in each sample: temperature, pH, electrical conductivity, total dissolved solids, total hardness as CaCO₃, calcium, magnesium, sodium, potassium, bicarbonate, carbonate, chloride, sulphate, nitrate, phosphate, silica, iron and manganese. All laboratory work was carried out in the Department of Earth Sciences and the Department of Civil Engineering, Annamalai University, Chidambaram. Because these laboratories lie within Cuddalore district, and therefore within the study area itself, the interval between collection and analysis was short, which is of material benefit for the unstable Parameter. Three instruments were used. Temperature, pH and electrical conductivity were obtained in the field with the multiparameter probe described in Section 3.3. Sodium and potassium were determined on an ELICO CL378 microprocessor-controlled flame photometer operating on liquefied petroleum gas and oil-free dry air with a silicon photodiode detector. Sulphate, nitrate, phosphate, silica, iron and manganese were determined colorimetrically on a Shimadzu UV-1800 ultraviolet-visible spectrophotometer covering 190 to 1100 nm at a spectral bandwidth of 1 nm. The remaining Parameter, namely total dissolved solids, total hardness, calcium, magnesium, alkalinity and chloride, require no instrumentation beyond a balance and a burette and were determined gravimetrically or titrimetrically. Procedures followed APHA (2023) throughout, and correspond to those applied in earlier hydrogeochemical work within this basin (Prasanna et al., 2009, 2010) and in recent assessments of comparable surface and coastal waters in southern India and elsewhere (Fentahun et al., 2023; Vijayakumar et al., 2024; Promilton et al., 2025; Cai et al., 2026).

2.4 Data quality assurance

The internal consistency of the completed data set was verified before any interpretation was attempted, following the practice adopted in recent hydrochemical assessments (Fentahun et al., 2023; Cai et al., 2026). Major ion concentrations were converted to milliequivalents per litre using the equivalent weights 20.04 for Ca²⁺, 12.153 for Mg²⁺, 22.99 for Na⁺, 39.098 for K⁺, 35.453 for Cl⁻, 48.03 for SO₄²⁻, 61.016 for HCO₃⁻, 30.005 for CO₃²⁻ and 62.004 for NO₃⁻, and the charge balance error was computed as

$$\text{CBE (\%)} = 100 \times (\Sigma \text{ cations} - \Sigma \text{ anions}) / (\Sigma \text{ cations} + \Sigma \text{ anions}) \quad (1)$$

where the summations are expressed in milliequivalents per litre. Charge balance errors ranged from -1.99% to +3.13% with a mean of +0.62%, so that all 38 samples fall within the ±5% criterion conventionally required before hydrochemical data are interpreted, and no sample was rejected. Two further checks were applied. Measured total hardness was compared with the value calculated as 2.497Ca + 4.118Mg and agreed to within ±1.2%, which confirms both the internal consistency of the three titrations and the absence of any appreciable contribution to hardness from Parameter other than calcium and magnesium.

2.5 Water quality indices

Three indices were computed, each directed at a distinct use and each employing a Parameters set and weighting scheme appropriate to that use. The drinking and domestic indices are expressed upon a pollution scale, on which increasing values denote deteriorating quality, whereas the irrigation index is expressed upon a quality scale, on which increasing values denote improving quality.

2.5.1 Drinking Water Quality Index

The Drinking Water Quality Index was computed by the weighted arithmetic method of Brown et al. (1972) over 13 Parameter, assessed against the acceptable limits of BIS (2012). A relative weight was assigned to each Parameters from a weight w_i of 1 to 5 reflecting its health and aesthetic significance, following the approach of Vasanthavigar et al. (2010):

$$W_i = w_i / \sum w_i \quad (2)$$

The quality rating for each Parameters was obtained as

$$q_i = 100 \times (C_i - V_o) / (S_i - V_o) \quad (3)$$

in which C_i is the measured concentration, S_i the standard and V_o the ideal value, taken as 7.0 for pH and zero for all other Parameter. The index is the weighted sum

$$DWQI = \sum (W_i \times q_i) \quad (4)$$

Samples were classified as Excellent below 50, Good from 50 to 100, Poor from 100 to 200, Very poor from 200 to 300 and Unsuitable for drinking above 300. The Parameter, standards and weights are given in Table 1. The conventional formulation, in which the unit weight is taken as inversely proportional to the standard, was evaluated and rejected for this dataset. Because the permissible limits for manganese and iron are numerically the smallest within the parameter set, that formulation assigns them 73.9% and 24.6% of the total weight respectively, leaving 1.5% for all major ions combined, and the resulting index correlates with manganese at $r = 0.98$. An entropy-weighted index was computed independently from the variance structure of the data as a check upon the subjective weighting, the information entropy of each Parameters being obtained from the normalised data matrix and the entropy weight from

$$w_{ej} = (1 - e_j) / \sum (1 - e_j) \quad (5)$$

where e_j is the information entropy of Parameters j . The two schemes reproduce the same ranking at a Spearman correlation of 0.98.

2.5.2 Domestic Water Quality Index

No standardised index exists for domestic use, and the Domestic Water Quality Index applied here is an explicit adaptation of the weighted arithmetic method, constructed so that it may be reproduced or reweighted. Equations 3 to 5 were applied unchanged, but over a Parameters set restricted to those governing non-potable household use, namely scaling, soap consumption, the staining of laundry and sanitary ware, and the corrosion of distribution fittings. Nine Parameter were included: total hardness, iron and manganese at $w_i = 5$, total dissolved solids and chloride at 4, sulphate, alkalinity as CaCO_3 and pH at 3, and sodium at 2, giving $\sum w_i = 34$. Calcium and magnesium were excluded in order to avoid double counting within total hardness. Alkalinity as CaCO_3 was computed as $0.8202\text{HCO}_3 + 1.6668\text{CO}_3$. Class boundaries follow those of the drinking index.

Scaling and corrosion potential were additionally assessed through two established engineering indices. The Langelier Saturation Index (Langelier, 1936) and the Ryznar Stability Index (Ryznar, 1944) were computed as

$$\text{LSI} = \text{pH} - \text{pH}_s \quad \text{and} \quad \text{RSI} = 2\text{pH}_s - \text{pH} \quad (6)$$

in which the saturation pH is given by

$$\text{pH}_s = (9.3 + A + B) - (C + D) \quad (7)$$

with $A = (\log_{10} \text{TDS} - 1)/10$, $B = -13.12 \log_{10}(T + 273.15) + 34.55$, $C = \log_{10}(\text{Ca as } \text{CaCO}_3) - 0.4$ and $D = \log_{10}(\text{alkalinity as } \text{CaCO}_3)$, where T is the water temperature in degrees Celsius and calcium as CaCO_3 is obtained as 2.497Ca .

2.5.3 Irrigation Water Quality Index

The Irrigation Water Quality Index of Meireles et al. (2010) was computed from five parameters, namely electrical conductivity, sodium adsorption ratio, sodium, chloride and bicarbonate, the last taken as the sum of bicarbonate and carbonate in milliequivalents per litre. The published weights were applied: 0.211 for electrical conductivity, 0.204 for sodium, 0.202 for bicarbonate, 0.194 for chloride and 0.189 for the sodium adsorption ratio. The quality measurement value of each parameter was obtained by linear interpolation within the limiting-value bands of the method,

$$q_i = q_{i\max} - [(x_{ij} - x_{inx}) \times q_{i\text{amp}} / x_{\text{amp}}] \quad (8)$$

in which $q_{i\max}$ is the upper limit of the quality band, x_{ij} the measured value, x_{inx} the lower limit of the concentration band within which the value falls, $q_{i\text{amp}}$ the amplitude of the quality band and x_{amp} the amplitude of the concentration band. The index is the weighted sum

$$\text{IWQI} = \sum (q_i \times w_i) \quad (9)$$

Samples were classified as No restriction from 85 to 100, Low restriction from 70 to 85, Moderate restriction from 55 to 70, High restriction from 40 to 55 and Severe restriction below 40.

2.4 Irrigation suitability indices

Nine classical indices were computed alongside the Irrigation Water Quality Index, all from concentrations expressed in milliequivalents per litre. The sodium adsorption ratio, sodium percentage, soluble sodium percentage, residual sodium carbonate, permeability index, magnesium hazard, Kelly's ratio and the chloro-alkaline indices were obtained as follows:

$$\text{SAR} = \text{Na} / \sqrt{\left[\frac{\text{Ca} + \text{Mg}}{2} \right]} \quad (10)$$

$$\text{Na}\% = 100 (\text{Na} + \text{K}) / (\text{Ca} + \text{Mg} + \text{Na} + \text{K}) \quad (11)$$

$$\text{RSC} = (\text{HCO}_3^- + \text{CO}_3^{2-}) - (\text{Ca} + \text{Mg}) \quad (12)$$

Table 1. Parameter, standards and weights applied in the three water quality indices. Weights for the drinking and domestic indices are relative weights w_i on a scale of 1 to 5, normalised to $\sum w_i = 41$ and 34 respectively; weights for the irrigation index are those published by Meireles et al. (2010) and sum to 1.000.

Parameters	Unit	BIS acceptable	WHO value
pH	–	6.5 to 8.5	6.5 to 8.5
Electrical conductivity	$\mu\text{S}/\text{cm}$	ns	ns
Total dissolved solids	mg/L	500	1,000*
Total hardness, CaCO_3	mg/L	200	500*
Calcium	mg/L	75	ns
Magnesium	mg/L	30	ns
Sodium	mg/L	ns	200*
Potassium	mg/L	ns	ns
Bicarbonate	mg/L	ns	ns
Chloride	mg/L	250	250*
Sulphate	mg/L	200	250*
Nitrate	mg/L	45	50
Iron	mg/L	0.3	0.3*
Manganese	mg/L	0.1	0.08
Sodium adsorption ratio	–	ns	ns

$$\text{PI} = 100 (\text{Na} + \sqrt{\text{HCO}_3^-}) / (\text{Ca} + \text{Mg} + \text{Na}) \quad (13)$$

$$\text{MH} = 100 \text{Mg} / (\text{Ca} + \text{Mg}) \quad (14)$$

$$\text{KR} = \text{Na} / (\text{Ca} + \text{Mg}) \quad (15)$$

$$\text{CAI} - 1 = [\text{Cl} - (\text{Na} + \text{K})] / \text{Cl} \quad (16)$$

Samples were classified upon the salinity and sodium hazard diagram of Richards (1954), the sodium hazard boundaries being taken at the conventional fixed thresholds of SAR 10, 18 and 26, and upon the classification of Wilcox (1955) relating electrical conductivity to sodium percentage. Restriction on use was additionally assessed against the criteria of Ayers and Westcot (1985). Residual sodium carbonate was interpreted following Eaton (1950), the permeability index following Doneen (1964), Kelly's ratio following Kelly (1963) and the chloro-alkaline indices following Schoeller (1965). Total hardness was classified following Sawyer and McCarty (1967).

The contribution of seawater to the saline samples was estimated from chloride as a conservative tracer, the mixing fraction being computed against a seawater chloride concentration of 19,350 mg/L, and was evaluated alongside the Na/Cl and Mg/Ca molar ratios and the ratio of chloride to total anions.

3.2 Statistical and geospatial analysis

Descriptive statistics comprising the minimum, maximum, mean, standard deviation and coefficient of variation were computed for all parameters in order to summarise the central tendency and the dispersion of each distribution. Several parameters return coefficients of variation above 100%, which indicates pronounced right skew rather than a normal distribution, and the correlation structure was therefore examined through two complementary measures rather than one. The Pearson product-moment coefficient was computed first, for which the critical values at $n = 38$ are 0.320 at $p < 0.05$ and 0.413 at $p < 0.01$, and the Spearman rank coefficient was then computed in parallel, since it depends only upon the order of the observations and is consequently unaffected by skew and insensitive to the leverage exerted by the few highly saline samples at the seaward end of the gradient. The two were compared parameter by parameter and any material divergence between them is reported, a Pearson coefficient substantially lower than its Spearman counterpart being diagnostic of a relationship that is monotonic but not linear, so that reporting both guards against the acceptance of a spurious

linear association generated by a few extreme values and equally against the dismissal of a real association merely because its form is curved. The resulting correlation matrix is presented as a heat map. Descriptive statistics and both correlation matrices were computed in Microsoft Excel and independently verified in IBM SPSS Statistics, agreement between the two being required before any coefficient was interpreted. The spatial distribution of each parameter and of the three water quality indices was then interpolated across the basin from the 38 sampling points and rendered as a thematic map in QGIS version 3.22. Sampling coordinates were recorded in the field in the WGS 84 geographic reference system and were projected to WGS 84 UTM Zone 44N, the zone within which the basin falls, so that distances and areas are preserved and the interpolation operates upon metric rather than angular separations. Surfaces were generated by inverse distance weighting, which is appropriate to a network of this size because it is an exact interpolator that honours the measured value at each sampling point and requires no assumption about the underlying variogram, an assumption that 38 points would in any case be too few to support. The interpolated surfaces were clipped to the basin boundary so that no value is portrayed beyond the extent sampled, and a common class interval was applied to each index so that the three maps may be read against one another.

3. Results and Discussion

3.1 Hydrochemistry

Descriptive statistics for the eighteen parameters are summarised in Table 2. Electrical conductivity ranged from 284 to 8,788 $\mu\text{S}/\text{cm}$ and total dissolved solids from 169 to 5,755 mg/L, while chloride ranged from 21 to 2,909 mg/L and sodium from 15.7 to 1,650 mg/L. Coefficients of variation exceeded 100% for electrical conductivity, total dissolved solids, sodium, chloride, magnesium, potassium, sulphate, carbonate, nitrate and phosphate, indicating strongly right-skewed distributions rather than normal ones.

A second group of parameters varied far less. pH remained between 7.01 and 8.07 and temperature between 26.8 and 30.2 °C, both with coefficients of variation below 3%, so neither discriminates between sampling locations in this data set. Silica (11.4 to 34.5 mg/L), bicarbonate (118 to 405 mg/L), iron (0.12 to 1.02 mg/L) and manganese (0.038 to 0.264 mg/L) varied by less than a factor of four. The contrast in dispersion between the two groups indicates that the measured parameters do not all respond to the same control.

Relative to the acceptable limits of BIS (2012), the most frequent exceedances were iron and total hardness in 18 samples each, total dissolved solids in 17, calcium in 16, magnesium in 13 and chloride in 11 (Table 2). Exceedances of the permissible limits were restricted to six samples for total dissolved solids, total hardness and chloride, five for magnesium and three for sulphate. Because BIS permits no relaxation of the 0.3 mg/L limit for iron, all 18 iron exceedances remain disqualifying. Nitrate exceeded both the Indian and the WHO limits at one location only.

Table 2. Descriptive statistics for the eighteen parameters measured in the 38 surface water samples, with the acceptable limits of BIS (2012) and the values of WHO (2022).

Parameter (unit)	Min	Max	Mean	SD	CV (%)	BIS	WHO	n > BIS
pH (-)	7.01	8.07	7.57	0.22	2.8	6.5-8.5	6.5-8.5	0
Electrical conductivity ($\mu\text{S}/\text{cm}$)	284	8,788	1,763	2,435	138.1	-	-	-
Total dissolved solids (mg/L)	169	5,755	1,123	1,609	143.3	500	1000	17
Total hardness as CaCO_3 (mg/L)	107	1,255	353	327	92.5	200	500	18
Calcium (mg/L)	28	140	68	37	54.0	75	-	16
Magnesium (mg/L)	9	220	44	59	133.7	30	-	13
Sodium (mg/L)	16	1,650	266	474	178.3	-	200	-
Potassium (mg/L)	4.5	88.5	26.3	26.6	100.9	-	-	-
Bicarbonate (mg/L)	118	405	251	99	39.5	-	-	-
Carbonate (mg/L)	0.007	1.191	0.237	0.273	115.4	-	-	-
Chloride (mg/L)	21	2,909	441	835	189.3	250	250	11
Sulphate (mg/L)	16	497	114	140	123.4	200	250	6
Nitrate (mg/L)	1.6	67.4	11.2	12.7	113.4	45	50	1
Phosphate (mg/L)	0.022	0.994	0.211	0.221	104.5	-	-	-
Iron (mg/L)	0.124	1.023	0.346	0.166	47.9	0.3	0.3	18

Manganese (mg/L)	0.038	0.264	0.085	0.041	47.9	0.1	0.08	9
Silica (mg/L)	11.4	34.5	21.4	7.4	34.8	-	-	-
Temperature (°C)	26.8	30.2	28.4	0.8	2.9	-	-	-

3.3 Spatial distribution and controls on composition

The interpolated distributions of the eighteen parameters are presented in Figures 2 to 4 and their variation between the three reaches is summarised in Figure 5. Electrical conductivity ranged from 284 to 508 $\mu\text{S}/\text{cm}$ in the upper reach, from 498 to 1,080 $\mu\text{S}/\text{cm}$ in the middle reach and from 1,038 to 8,788 $\mu\text{S}/\text{cm}$ in the lower reach, so the three reaches are almost completely separated on this parameter. Position along the channel, rather than water body type, is therefore the principal discriminant of composition in this data set. Electrical conductivity, total dissolved solids, chloride, sodium, magnesium, potassium, sulphate, calcium and total hardness showed a common pattern of low and uniform values across the western two thirds of the basin followed by a marked increase within the final 10 to 15 km before the coast (Figures 2c, 2d, 4c and 4e). The reach-wise distributions in Figures 5a to 5e show interquartile ranges that scarcely overlap between adjacent reaches.

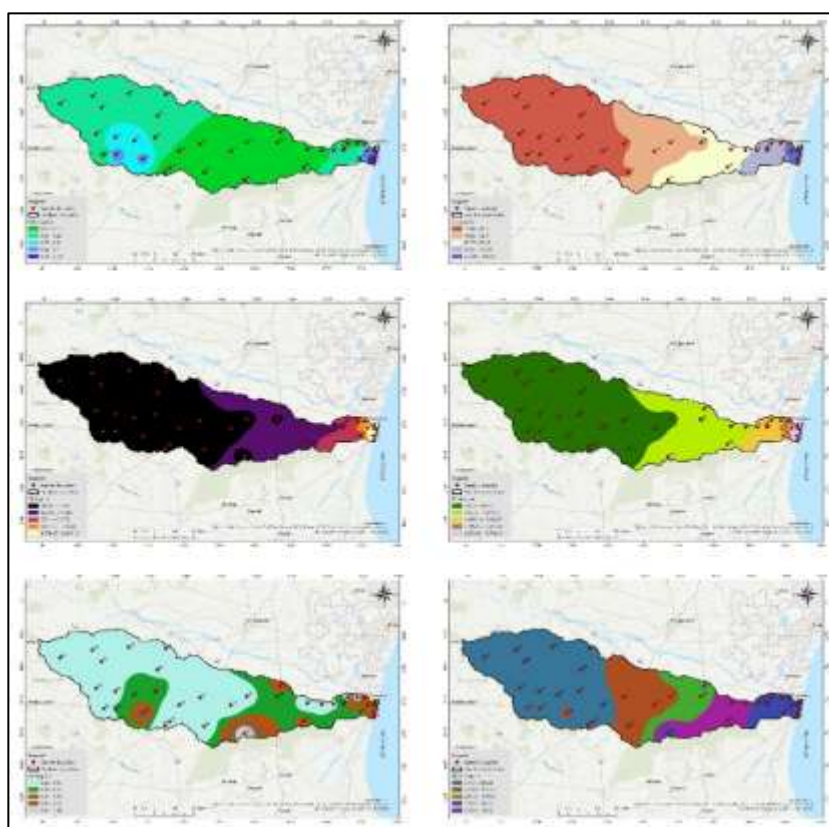


Fig. 2. Spatial distribution of (a) carbonate, (b) calcium, (c) chloride, (d) electrical conductivity, (e) iron and (f) bicarbonate across the Gadilam river basin. Surfaces were interpolated from the 38 sampling points by inverse distance weighting. Concentrations are in mg/L except electrical conductivity which is in $\mu\text{S}/\text{cm}$.

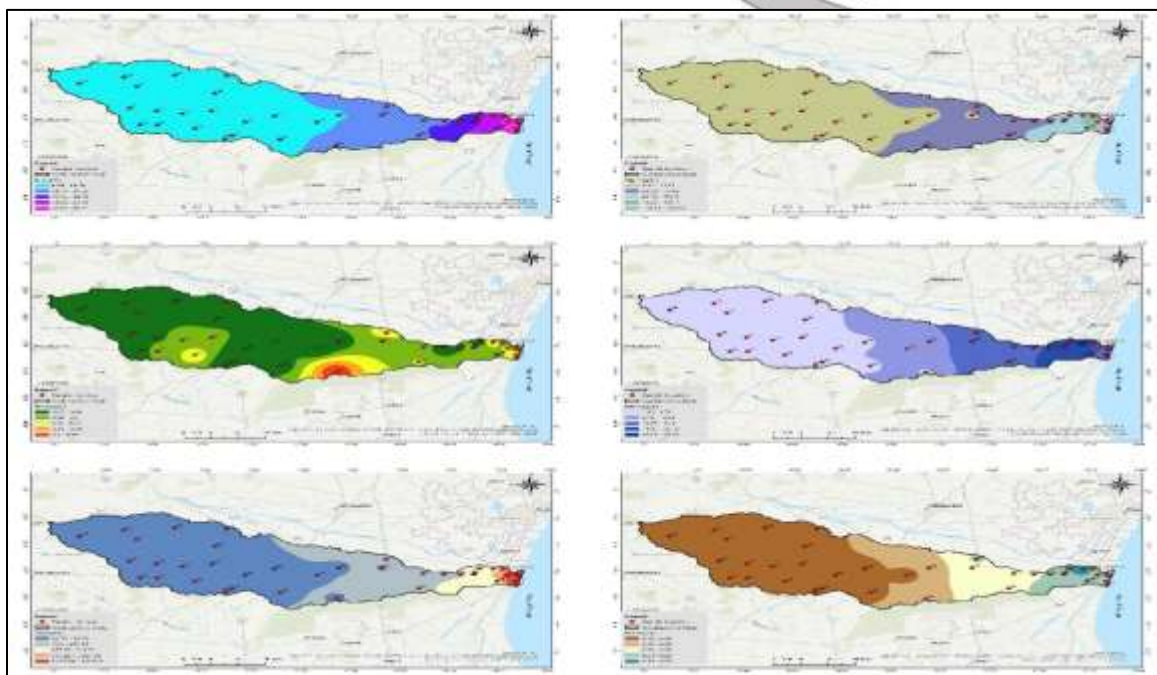


Fig. 3. Spatial distribution of (a) potassium, (b) magnesium, (c) manganese, (d) nitrate, (e) sodium and (f) phosphate across the Gadilam river basin. Surfaces were interpolated from the 38 sampling points by inverse distance weighting. All concentrations are in mg/L.

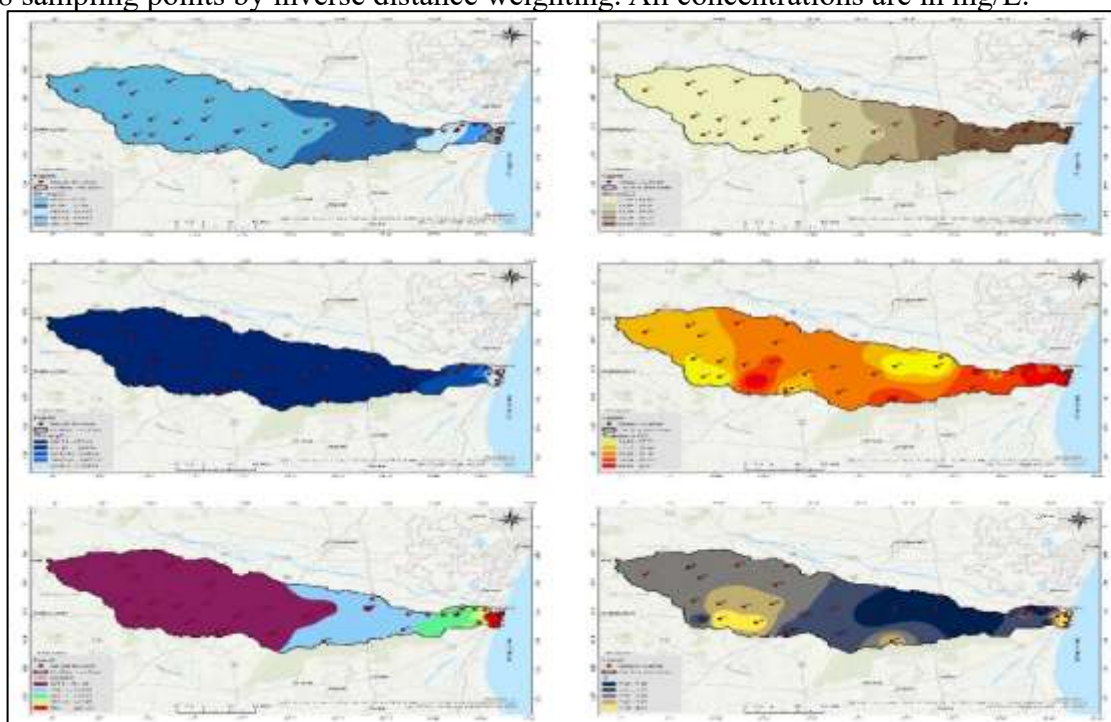


Fig. 4. Spatial distribution of (a) sulphate, (b) silica, (c) total dissolved solids, (d) temperature, (e) total hardness and (f) pH across the Gadilam river basin. Surfaces were interpolated from the 38 sampling points by inverse distance weighting. Concentrations are in mg/L with hardness expressed as CaCO_3 , and temperature in $^{\circ}\text{C}$.

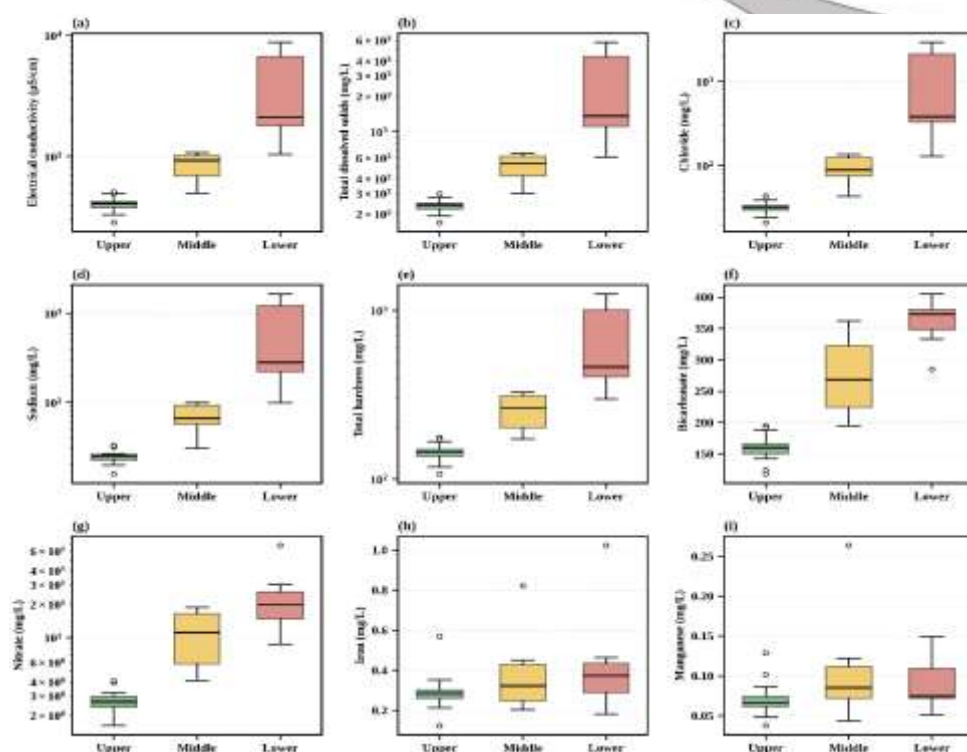


Fig. 5.a Reach-wise distribution of (a) electrical conductivity, (b) total dissolved solids, (c) chloride, (d) sodium, (e) total hardness, (f) bicarbonate, (g) nitrate, (h) iron and (i) manganese.

The relative magnitude of the increase differs between solutes. Sodium increased 28-fold and chloride 37-fold between the upper and the lower reach, whereas calcium increased 3-fold and bicarbonate 2.3-fold (Figures 5d and 5f). The disproportionate enrichment of sodium and chloride relative to the weathering-derived ions is consistent with mixing between the river water and a saline end member, and comparable downstream enrichment has been reported for groundwater in this basin (Prasanna et al., 2011) and for other coastal aquifers along the Tamil Nadu coast (Vijayakumar et al., 2024).

Two ionic ratios were examined to test this interpretation. Figure 6a plots sodium against chloride on an equivalent basis and shows the samples approaching the seawater reference line as salinity increases. The Na/Cl molar ratio decreased from 1.26 in the headwater tanks to between 0.869 and 0.892 in the estuary and the backwater, converging on the seawater value of 0.858, and chloride-based mixing fractions reached 15.0% in the backwater and 14.6% in the estuary. These ratios are consistent with a marine contribution to the lower reach, although a single sampling occasion cannot establish the relative roles of tidal ingress and longer-term saline intrusion.

Bicarbonate did not follow this pattern. It increased by a factor of only 2.3 and its interpolated surface is patchy rather than graded towards the coast (Figure 2f). Silica behaved similarly, with a mean of 14.4 mg/L in the upper reach and 29.5 mg/L in the lower reach (Figure 4b). Both are minor constituents of seawater, so their limited enrichment is consistent with a catchment-derived rather than a marine origin.

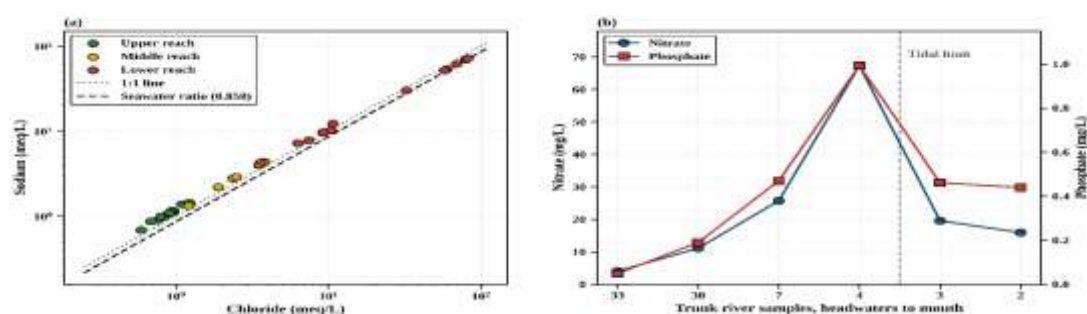


Fig. 6. (a) Sodium against chloride on an equivalent basis, with the 1:1 line and the seawater ratio of 0.858 shown for reference. (b)

Nitrate and phosphate attained their maxima within the lower reach (Figures 3d and 3f), but the longitudinal transect along the trunk river in Figure 6b shows that the pattern differs from that of the salinity parameters. Nitrate increased downstream from 4.07 mg/L at sample 33, through 11.13 mg/L at sample 30 and 25.74 mg/L at sample 7, to a maximum of 67.36 mg/L at sample 4, and then decreased to 19.58 mg/L at sample 3 and 15.95 mg/L at sample 2, the two most saline river samples. Phosphate followed the same trajectory, increasing from 0.05 to 0.99 mg/L before decreasing to 0.46 and 0.44 mg/L. A concentration maximum located upstream of the most saline samples, followed by a decrease towards the river mouth, is not the pattern expected if nutrients were supplied by the marine end member, for which concentrations would be expected to increase seaward. The observed distribution is therefore more consistent with inputs originating within the catchment upstream of the tidal limit. The present data set does not include land use, discharge inventory or isotopic information, and the specific sources cannot be identified from the hydrochemistry alone. Downstream nitrate accumulation has nonetheless been reported in other Indian river basins (Verma et al., 2023), and elevated nutrient concentrations in impounded water bodies have been attributed to long residence times (Giblin et al., 2026). Iron and manganese showed no systematic variation along the basin. Iron averaged 0.29, 0.39 and 0.40 mg/L across the upper, middle and lower reaches and manganese averaged 0.07, 0.11 and 0.09 mg/L, and the reach-wise distributions in Figures 5h and 5i overlap almost completely.

The interpolated surfaces in Figures 2e and 3c show isolated areas of elevated concentration superimposed on an otherwise uniform background, the highest manganese value of 0.264 mg/L occurring at sample 24, which also recorded the highest iron concentration among the lake samples at 0.823 mg/L. The absence of covariation with salinity indicates that the distribution of these two metals is governed by a control that operates independently of the longitudinal gradient. Redox conditions are a plausible control, but neither redox potential nor dissolved oxygen was measured in this campaign and the mechanism cannot be confirmed from the present data.

3.4 Pearson correlation matrix

The Pearson correlation matrix for the eighteen parameters is presented in Figure 7. For $n = 38$ the critical values are 0.320 at $p < 0.05$ and 0.413 at $p < 0.01$. Three groups of mutually correlated parameters are evident. The first comprises electrical conductivity, total dissolved solids, sodium, chloride, magnesium, potassium, sulphate and total hardness, within which every pairwise coefficient exceeds 0.92 and several approach unity (Na-Cl, $r = 1.000$; EC-TDS, $r = 1.000$). Such coefficients indicate that these eight parameters carry largely redundant information and are consistent with their joint response to a single salinity gradient.

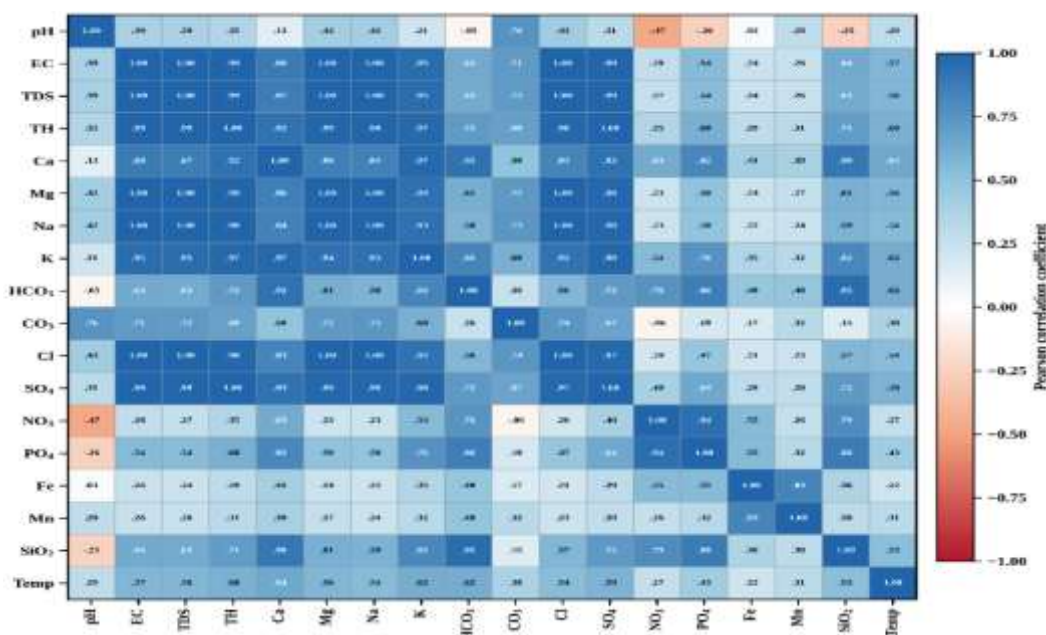


Fig. 7. Pearson correlation matrix for the eighteen measured parameters. For $n = 38$ the critical values are 0.320 at $p < 0.05$ and 0.413 at $p < 0.01$.

The second group comprises bicarbonate, silica and calcium. Bicarbonate correlated with silica at $r = 0.947$ and calcium with silica at $r = 0.902$, while bicarbonate correlated only moderately with electrical conductivity ($r = 0.63$). The association of calcium with both groups ($r = 0.88$ with electrical conductivity and 0.92 with bicarbonate) suggests that calcium may receive contributions from more than one source, although the correlation structure alone does not allow these contributions to be quantified.

The third group is the iron and manganese pair, which correlated with one another at $r = 0.828$ but with electrical conductivity at only 0.243 and 0.257 , neither significant at $p < 0.01$. This statistical separation is consistent with the spatial independence described in Section 4.2. The nutrients require a separate comment. Nitrate and phosphate correlated at $r = 0.942$, but their Pearson correlations with electrical conductivity were weak (0.277 and 0.542) whereas the corresponding Spearman coefficients were 0.834 and 0.920 . The divergence arises because nutrient concentrations increase monotonically in rank along the channel while decreasing in the two most saline samples, which depresses the linear coefficient; the transect in Figure 6b illustrates this behaviour. Across the full matrix the mean absolute difference between the Pearson and Spearman coefficients was 0.161 , with the nutrient pairs accounting for the largest discrepancies. Because eight parameters are mutually collinear above $r = 0.92$, the data set contains considerably fewer independent dimensions than parameters, and inferences drawn from the behaviour of individual samples should be treated accordingly.

3.5 Suitability for drinking

3.5.1 Compliance with the drinking water standards

Twenty of the 38 samples complied with the chemical limits of BIS (2012) and 18 did not. The failures fall into two groups that differ in cause and in the treatment they would require.

Salinity accounts for the first group. Six samples in the lower reach, comprising both backwaters, both estuary samples and river samples 2 and 3, simultaneously exceeded the permissible limits for total dissolved solids, chloride and total hardness. Total dissolved solids in these samples ranged from $2,563$ to $5,755$ mg/L against a permissible limit of $2,000$ mg/L and chloride from $1,150$ to $2,909$ mg/L against $1,000$ mg/L; five also exceeded the permissible limit for magnesium and three that for sulphate. Iron accounts for the second and larger group. All 18 non-compliant samples exceeded the acceptable limit of 0.3 mg/L, and in nine of them iron was the only disqualifying parameter. These nine comprise lakes 17, 18, 23, 24, 26, 28, 34 and 37 together with river 30, with iron between 0.31 and 0.82 mg/L and an otherwise compliant chemistry, and eight of them lie in the upper and middle reaches. Since BIS permits no relaxation for iron these samples are formally non-potable, although WHO (2022) sets no health-based guideline value for iron and reports only taste, colour and staining effects above 0.3 mg/L. Manganese is the parameter on which the two standards diverge most. No sample exceeded the BIS permissible limit of 0.3 mg/L and nine exceeded the acceptable limit of 0.1 mg/L, yet 15 samples exceeded the provisional health-based guideline value of 0.08 mg/L given by WHO (2022). Compliance assessed against the Indian specification alone would therefore not reflect this exceedance. Nitrate exceeded both standards at one location only, river sample 4, at 67.4 mg/L against 45 mg/L (BIS) and 50 mg/L (WHO).

3.5.2 Drinking Water Quality Index

The spatial distribution of the Drinking Water Quality Index is shown in Figure 8. Most of the upper reach falls within the Excellent class and the middle reach within the Good class, with values deteriorating through Poor and Very poor to Unsuitable over the final few kilometres before the coast. Across the data set, 17 samples (44.7%) were classified as Excellent, eight (21.1%) as Good, seven (18.4%) as Poor, one (2.6%) as Very poor and five (13.2%) as Unsuitable for drinking.

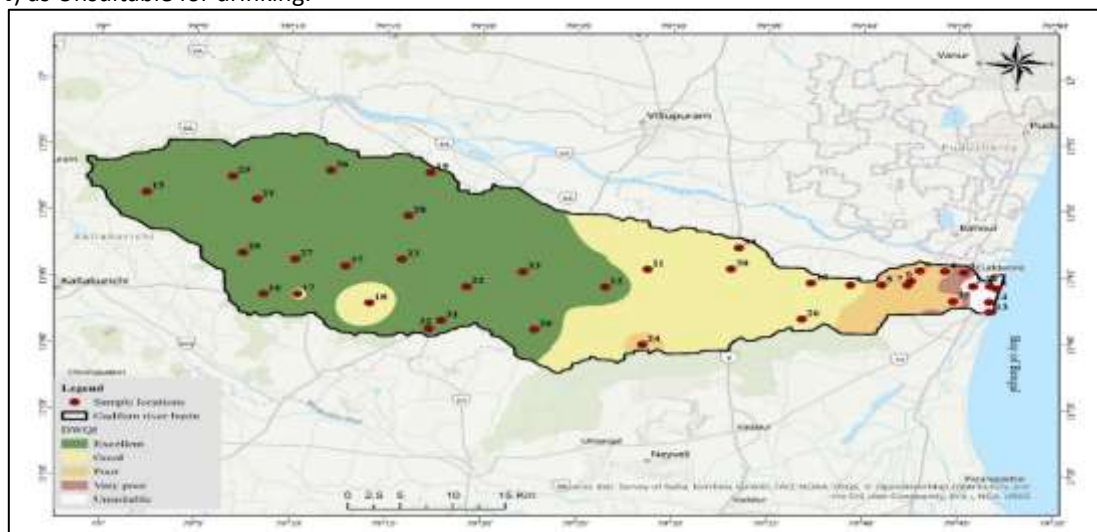


Fig. 8. Spatial distribution of the Drinking Water Quality Index across the Gadilam river basin, interpolated from the 38 sampling points by inverse distance weighting. Classes are Excellent below 50, Good from 50 to 100, Poor from 100 to 200, Very poor from 200 to 300 and Unsuitable above 300.

The index ranged from 28.8 at lake 16 to 466.1 at backwater 38, and reach means were 42.4, 73.8 and 241.9 for the upper, middle and lower reaches respectively. The ranked values and their class boundaries are shown in Figure 12a and the class distribution by reach in Figure 12b. The five Unsuitable samples comprise both backwaters, both estuary samples and river sample 2, with river sample 3 in the Very poor class. Two localised features of Figure 8 are not explained by the salinity gradient. A Good enclave surrounds samples 17 and 18 within the otherwise Excellent upper reach, and a Poor enclave occurs at sample 24 in the south-central basin. Sample 24 recorded the highest manganese and the second highest iron concentration in the data set and sample 18 the third highest iron, so these enclaves correspond to the iron and manganese distribution described in Section 4.2 rather than to salinity.

Two features of the index calculation affect interpretation. When unit weights are assigned in inverse proportion to the standard, manganese and iron absorb 73.9% and 24.6% of the total weight because their limits are numerically the smallest in the parameter set; the resulting index correlates with manganese at $r = 0.98$ and classifies backwater sample 38 (5,755 mg/L total dissolved solids) as Good while classifying lake sample 24 (538 mg/L) as Very poor. The index reported here therefore uses relative weights based on health and aesthetic significance (Brown et al., 1972; Vasanthavigar et al., 2010). An entropy-weighted index computed from the variance structure of the data reproduced the same ranking at a Spearman coefficient of 0.98, indicating that the classification is not sensitive to the choice between the two weighting schemes (Gautam et al., 2022). The index is also compensatory, so a single disqualifying exceedance may be offset by compliant parameters. River sample 4 returned an index value of 178.7, placing it in the Poor rather than the Unsuitable class, although its nitrate concentration exceeds a limit for which no relaxation is permitted. Potability was therefore determined by direct comparison against the BIS limits, with the index used to rank and map relative quality.

3.6 Suitability for domestic use

Household use is governed by scaling, soap consumption, staining and the corrosion of distribution fittings, none of which is represented in a drinking water index. The Domestic Water Quality Index defined in Section 3.5.2 was therefore computed over nine parameters of household relevance. Hardness is the principal constraint. On the classification of Sawyer and McCarty (1967), 15 samples were very hard (above 300 mg/L as CaCO_3), 11 hard (150 to 300 mg/L) and 12 moderately hard (75 to 150 mg/L), with no soft samples. The hardness surface in Figure 4e shows 107 to 225 mg/L across the upper reach and 848 to 1,255 mg/L in the coastal tract. Eighteen samples exceeded 200 mg/L and six exceeded 500 mg/L. Iron and manganese affect a wider area than hardness because, as shown in Section 4.2, their distribution is not confined to the lower reach. Eighteen samples exceeded 0.3 mg/L of iron and 15 exceeded 0.08 mg/L of manganese, while 37 of the 38 samples exceeded 0.02 mg/L of manganese, the concentration above which WHO (2022) reports staining and pipe deposits. The Domestic Water Quality Index classified six samples (15.8%) as Excellent, 18 (47.4%) as Good, eight (21.1%) as Poor, one (2.6%) as Very poor and five (13.2%) as Unsuitable (Figure 9). Comparison with Figure 8 shows that the two indices agree on the coastal deterioration but differ across the upper reach, where the domestic index places most samples in the Good class and reserves Excellent for four small areas around samples 15, 16 and 29, 31 and 32, and 12. Of the 21 lake samples, 15 were Excellent for drinking but only five were Excellent for domestic use (Figure 12b). This difference follows from the weighting. Iron, manganese and hardness together carry 44% of the weight in the domestic scheme against 27% in the drinking scheme. Averaged across the data set, hardness contributed 21.1% of the domestic index value, iron 19.7%, total dissolved solids 15.4% and manganese 14.5%, and iron was the largest single contributor in 20 of the 38 samples and hardness in 12. Water that meets the chemical limits for drinking may therefore still present staining and scaling problems in household use, and the two indices should be reported separately rather than one being inferred from the other.

Scaling and corrosion potential were assessed through the Langelier Saturation Index (Langelier, 1936) and the Ryznar Stability Index (Ryznar, 1944). The estuary and backwater samples were scale forming, with Langelier values of +0.84 to +1.00 and Ryznar values of 5.94 to 6.16, while the upper and middle reach samples were mildly corrosive, with Ryznar values of 6.8 to 8.7 and Langelier values close to or slightly below zero. Across the data set 28 samples were balanced and eight scale forming on the Langelier criterion, while the Ryznar index classified 25 as corrosive and five as scale forming. Pipe material selection in the upper basin and scale management in the coastal tract would therefore require different specifications.

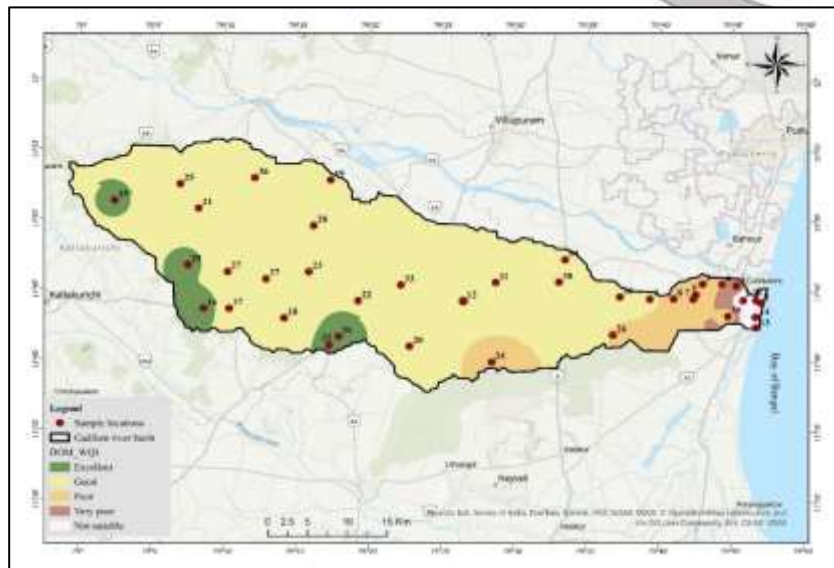


Fig. 9. Spatial distribution of the Domestic Water Quality Index across the Gadilam river basin, interpolated from the 38 sampling points by inverse distance weighting. The index is weighted over nine parameters of household relevance and the class boundaries follow those of the drinking index.

3.7 Suitability for irrigation

3.7.1 Salinity and sodium hazard

On the diagram of Richards (1954) in Figure 10a the samples occupy a single band extending from C2-S1 to C4-S3. Twenty-one samples (55.3%) plot in the medium salinity and low sodium field C2-S1, eleven (28.9%) in C3-S1, three in C4-S2 and three in C4-S3. The samples do not occupy the fields combining high sodium with low salinity, or the converse. The classification of Wilcox (1955) in Figure 10b reproduces the same ordering and places the upper and middle reach samples within the excellent to good field. Sodium hazard is low across most of the basin. Thirty-two of the 38 samples fall within the S1 class with a sodium adsorption ratio below 10, and the ratio becomes limiting only in the six marine-influenced samples of the lower reach, where it reaches a maximum of 20.3. Assessed against Ayers and Westcott (1985), 20 samples attract no restriction on use, twelve a slight to moderate restriction and six a severe restriction, so salinity rather than sodicity is the limiting factor in the freshwater reaches. Chloride toxicity to sensitive crops is rated severe in eight samples, a larger group than salinity alone identifies.

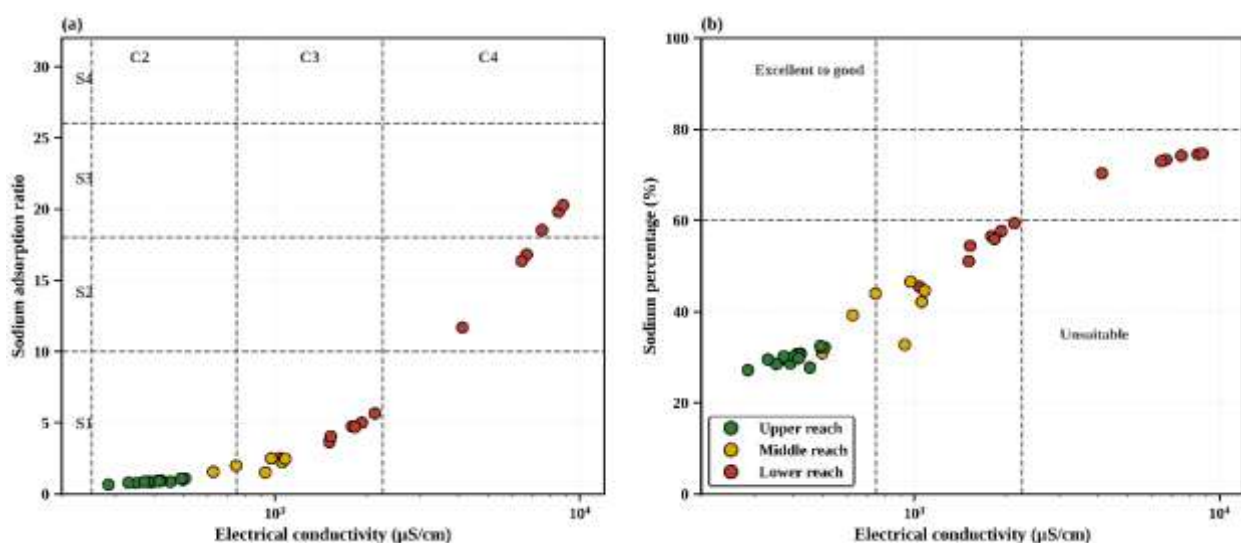


Fig. 10. Irrigation suitability of the surface waters: (a) salinity and sodium hazard diagram of Richards (1954) and (b) classification of Wilcox (1955) relating electrical conductivity to sodium percentage.

The classical suitability indices are summarised in Table 3. Residual sodium carbonate was negative in every sample, ranging from -0.20 to -19.59 meq/L, so on the criterion of Eaton (1950) no sample presents a residual alkalinity hazard. All 38 samples fall within permeability classes I or II of Doneen (1964), with values between 55% and 76%; the narrow range across a thirty-fold variation in salinity indicates that this index discriminates poorly in the present setting. Magnesium hazard exceeds the 50% threshold in the same six marine-influenced samples. Kelly's ratio (Kelly, 1963) exceeds unity in eleven samples and therefore identifies five more than the sodium percentage criterion, namely samples 4, 5, 6, 7 and 35, making it the more conservative of the two sodium measures in this data set. The chloro-alkaline indices (Schoeller, 1965) are positive in the saline samples, which is consistent with cation exchange, although the indices alone do not establish the exchange direction

Table 3. Irrigation suitability indices computed for the 38 surface water samples. Thresholds in the final column follow Richards (1954), Eaton (1950), Doneen (1964) and Kelly (1963).

Index	Minimum	Maximum	Mean	Samples outside the safe range
Sodium adsorption ratio	0.66	20.27	4.29	6 (>10)
Sodium percentage (%)	27.2	74.7	43.2	6 (>60)
Soluble sodium percentage (%)	23.2	72.4	38.7	6 (>60)
Residual sodium carbonate (meq/L)	-19.59	-0.20	-2.94	0 (>1.25)
Permeability index (%)	55.3	76.5	68.1	0 (<25)
Magnesium hazard (%)	34.1	72.3	41.6	6 (>50)
Kelly's ratio	0.32	2.86	0.90	11 (>1)
Chloro-alkaline index 1	-0.46	0.10	-0.27	not applicable
Chloro-alkaline index 2	-0.25	0.52	-0.05	not applicable

independently of the salinity gradient.

3.7.2 Irrigation Water Quality Index

The Irrigation Water Quality Index of Meireles et al. (2010) was computed from electrical conductivity, sodium adsorption ratio, sodium, chloride and bicarbonate, and its spatial distribution is shown in Figure 11. The index runs on a quality scale, so the pattern is inverted relative to Figures 8 and 9. All 18 upper reach samples fall within the No restriction class, the middle reach divides between No restriction and Low restriction, and values deteriorate through Moderate and High to Severe restriction across the lower reach (Figure 12c). Applied in its original published form the index placed 19 samples in High restriction, seven in Moderate, six in Low and six in Severe, and assigned no sample to the unrestricted class, which conflicts with the Richards (1954) classification of the same samples in Figure 10a.

The discrepancy originates in the lower bounds of the method. The quality measurement curves of Meireles et al. (2010) assign sub-index values between 0 and 35 to concentrations below the optimum range as well as above it, specifically sodium below 2 meq/L, chloride below 1 meq/L and a sodium adsorption ratio below 2. Most upper reach samples fall below all three bounds: their conductivity sub-indices lie between 93 and 98 but their sodium sub-indices fall to between 12 and 20 and their chloride sub-indices to between 21 and 34, which moves the aggregate index into the High restriction class. The lower bounds represent the infiltration hazard associated with water of very low electrolyte concentration, but Ayers and Westcot (1985) place that threshold below 0.2 dS/m whereas the minimum recorded in this basin was 0.28 dS/m.

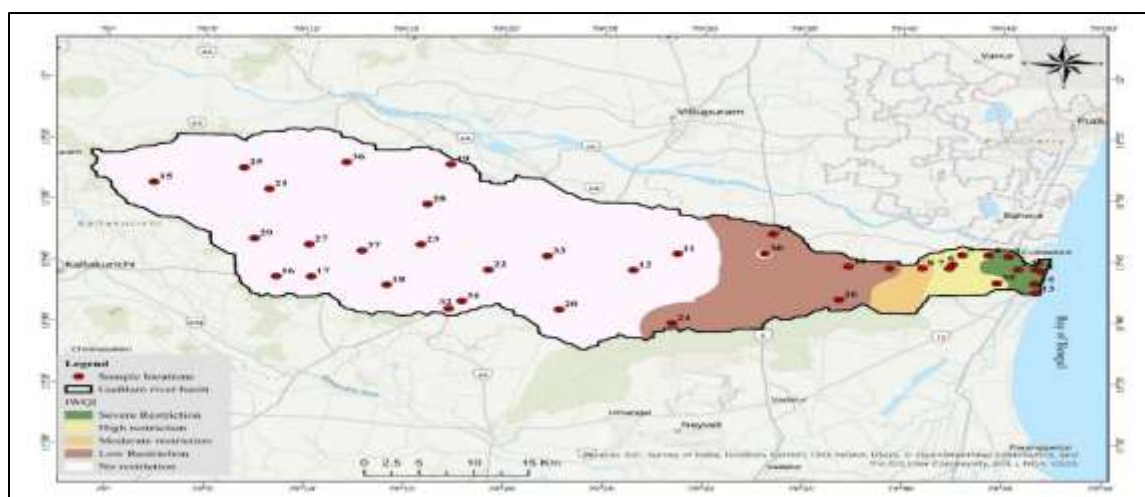


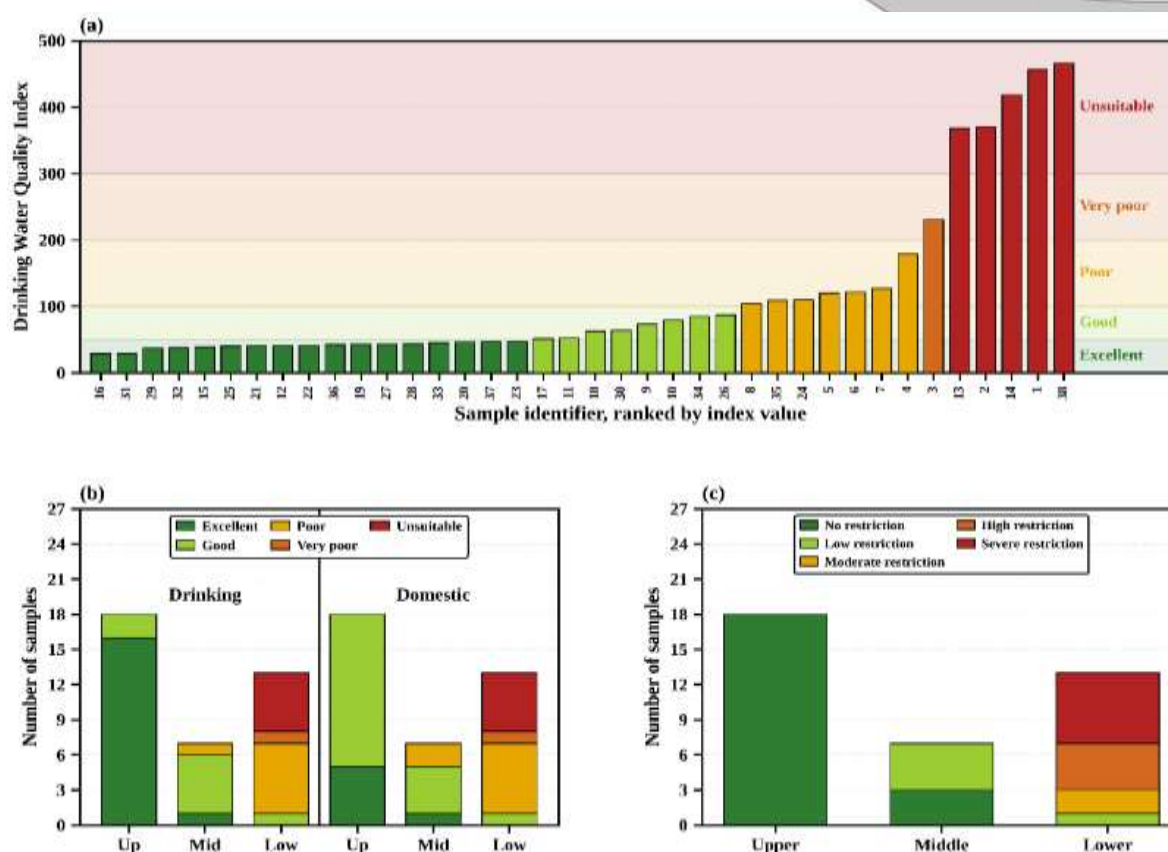
Fig. 11. Spatial distribution of the Irrigation Water Quality Index across the Gadilam river basin, interpolated from the 38 sampling points by inverse distance weighting.

The index was therefore also computed in an upper-bound form in which only concentrations above the optimum reduce the sub-index. In this form, mapped in Figure 11, 21 samples (55.3%) fall in the unrestricted class, five in Low restriction, two in Moderate, four in High and six in Severe restriction. The 21 unrestricted samples correspond to the set that the Richards (1954) diagram places in C2-S1, and this agreement between two independently constructed classifications supports the upper-bound form for this data set. Both forms are reported so that the results remain comparable with studies applying the index as originally published (Ghosh and Bera, 2023; Vyas et al., 2024). The treatment of concentrations below the lower bounds should be stated explicitly when the index is applied to dilute surface water.

3.8 Integrated assessment and management implications

The three indices converge at the extremes of the longitudinal gradient and diverge in its middle section. Figure 12 compares them, panel b giving the drinking and domestic classifications by reach and panel c the irrigation classification on the same basis. The drinking and domestic indices correlate at a Spearman coefficient of 0.995, since both respond to the same gradient, but the agreement conceals a systematic shift: 15 of the 21 lake samples are Excellent for drinking and only five for domestic use. The irrigation index correlates with the other two at -0.969 , which reflects its inverted scale rather than any independent information. The samples on which the three verdicts diverge are of greater practical interest. Lakes 17, 18, 23, 28 and 37 together with river 30 attract no irrigation restriction yet fail the drinking standard, and in each case iron is the only disqualifying parameter. These sources are usable for irrigation in their present condition, whereas their use for supply would require iron removal. A single-use assessment would not have distinguished these cases.

Three water quality concerns emerge from the combined results, each associated with a different group of locations. The first is iron and manganese, which affect samples across the whole basin rather than a single reach. Nine samples fail the drinking standard on iron alone, and iron and manganese are the principal contributors to the domestic index. Because these two parameters show no relationship with position along the channel, any treatment would be required at the point of abstraction rather than at a single location. The second concern is salinity in the lower reach. Samples 1, 2, 3, 13, 14 and 38 exceed the BIS permissible limits for total dissolved solids, chloride and hardness simultaneously and fall in the Severe restriction class for irrigation under both forms of the index. These sources are unsuitable for drinking, domestic and irrigation use without treatment capable of removing dissolved salts. The third concern is the nutrient maximum near river sample 4, where nitrate (67.4 mg/L) exceeds both drinking water standards and phosphate reaches 0.99 mg/L. The transect in Figure 6b places this maximum upstream of the most saline samples, which indicates that the source lies within the catchment. Identifying it would require a survey of land use and discharges in that part of the basin, which the present data set does not provide. Monitoring effort would be most usefully directed at these three situations: the saline lower reach, where the January 2026 sampling represents a post-monsoon condition and seasonal variation remains uncharacterised (Promilton et al., 2025); the vicinity of sample 4, where the nutrient maximum requires source identification; and iron and manganese at any source taken into supply. Four limitations should be noted. The assessment covers chemical quality only, since dissolved oxygen, biochemical oxygen demand and coliform counts were not determined. Fluoride and heavy metals were not measured. The campaign represents a single occasion, so the mixing fraction of approximately 15% in the lower reach should be read as a post-monsoon value rather than an annual figure. Finally, the statistical treatment was limited to bivariate correlation, and multivariate methods such as principal component or cluster analysis were not applied, so the number of independent controls is inferred from the correlation structure rather than formally resolved.



5. CONCLUSION

Thirty-eight surface-water samples collected across the Gadilam River Basin in January 2026 were assessed for drinking, domestic, and irrigation suitability using three separately weighted water-quality indices, supported by comparison with Indian and international standards and correlation analysis of 18 parameters. Water chemistry was found to vary primarily along the longitudinal gradient rather than among water-body types. Electrical conductivity increased from 284–508 $\mu\text{S}/\text{cm}$ in the upper reach to 1,038–8,788 $\mu\text{S}/\text{cm}$ in the lower reach, accompanied by 28-fold and 37-fold increases in Na^+ and Cl^- , respectively. The convergence of the Na/Cl molar ratio toward the seawater value (0.858) and chloride-based mixing estimates of up to 15.0% were consistent with a marine contribution to the lower reach. In contrast, nitrate and phosphate maxima were recorded upstream of the most saline locations, indicating predominantly catchment-derived inputs. Iron and manganese were strongly correlated ($r = 0.828$), but no significant relationship with salinity was observed, suggesting that their distribution was controlled independently of the longitudinal salinity gradient. Differences among the three indices demonstrated that water suitability was strongly dependent on the intended use and weighting methodology. Seventeen samples were classified as Excellent and five as Unsuitable for drinking, while 20 samples complied with the Indian chemical standards. Iron was identified as the largest contributor to the drinking-water index at 20 locations. Under the domestic-water classification, 15 of the 21 lakes were downgraded from Excellent to Good, reflecting the greater influence of hardness, staining, and scaling parameters. Six samples that exceeded the drinking-water limit for iron remained suitable for irrigation, indicating that drinking-water exceedances did not necessarily translate into irrigation restrictions. The influence of weighting methodology was also demonstrated: inverse-standard weighting assigned more than 98% of the total weight to manganese and iron and produced classifications that differed substantially from the measured water chemistry, whereas the adopted relative weighting showed a strong agreement with entropy-derived weights (Spearman $\rho = 0.98$).

Three principal water-quality concerns were identified. Elevated iron and manganese were observed across the basin and would require treatment where affected waters are intended for potable supply. High salinity resulted in six lower-reach samples being unsuitable for the assessed uses without desalination or other salt-removal treatment. A nitrate concentration of 67.4 mg/L recorded at river sample 4 indicated a localized nutrient concern, for which upstream source identification is warranted. Accordingly, monitoring should be prioritized for iron and

manganese, salinity in the lower reach, and nutrient enrichment near the identified upstream location. The findings should be interpreted in light of several limitations. The assessment was based on chemical parameters, with microbiological, redox, and selected trace-element measurements not included. As sampling was conducted during a single post-monsoon period, the estimated 15% marine mixing fraction represents seasonal rather than annual conditions. Furthermore, the statistical assessment was limited to bivariate relationships. Seasonal sampling with expanded chemical and microbiological analyses and multivariate approaches is therefore needed for a more comprehensive assessment.

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