

Integrated Groundwater Quality Index Mapping for Drinking Water Risk Assessment in Mangalvedha Taluka, Maharashtra, India: A Decadal GIS-Based Hydrochemical Investigation (2015–2024)

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Abstract: Groundwater is the principal source of potable supply in the drought-prone, semi-arid Mangalvedha Taluka of Solapur District, Maharashtra, where Deccan basaltic aquifers, intensive sugarcane–pulse cultivation and erratic monsoon rainfall combine to elevate drinking-water risk. This investigation develops an integrated Groundwater Quality Index (GWQI)–Geographic Information System (GIS) framework using 7,541 in-situ hydrochemical observations collected by the Groundwater Surveys and Development Agency (GSDA) from 86 villages of Mangalvedha Taluka across eight hydrological years (2016–17 to 2023–24). Thirteen physico-chemical parameters were considered (pH, EC, TDS, TH, Ca, Mg, Cl⁻, SO₄²⁻, HCO₃⁻-equivalent alkalinity, NO₃⁻, F⁻, Fe, turbidity). A Weighted Arithmetic Water Quality Index was computed against Bureau of Indian Standards (BIS) IS 10500:2012 desirable limits using subjective importance weights ($\Sigma w_i = 28$). The sample-level GWQI ranged from 5.15 to 827.24 (mean 105.81 ± 63.18); 9.72 % of samples qualified as Excellent, 49.48 % Good, 32.79 % Poor, 6.21 % Very Poor and 1.80 % Unsuitable. Aggregated village-mean indices identified one Excellent, 44 Good, 33 Poor and 4 Very Poor villages. K-means clustering delineated three risk zones: Safe (47 villages), Moderate-Risk (29 villages), and High-Risk (6 villages) — Dhavalas, Gharniki, Mallewadi, Tamdardi, Mahamadabad (Shetfal) and Dharamgaon — exhibiting mean TDS > 2,500 mg L⁻¹, total hardness > 1,000 mg L⁻¹ and nitrate > 90 mg L⁻¹. IDW spatial interpolation delineated two persistent contamination corridors aligned with the central-northern and south-eastern alluvial–weathered-basalt belts of the taluka. Mann–Kendall temporal trend analysis on yearly means did not detect statistically significant monotonic change ($p > 0.05$) in major indicators, but pronounced inter-annual variability driven by rainfall recharge dynamics was evident. Public-health implications include elevated risks of infant methaemoglobinaemia and renal/cardiovascular stress in the High-Risk Zone. The study recommends village-scale managed aquifer recharge, point-of-use defluoridation and denitrification at six priority habitations, periodic IS 10500 surveillance and a smart GIS dashboard for GSDA Solapur to operationalise the decision-support framework presented here.

Keywords: Groundwater Quality Index; Drinking Water Suitability; GIS Mapping; Risk Zoning; Hydrochemistry; Mangalvedha Taluka; Water Quality Assessment; Groundwater Governance.

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I. INTRODUCTION

Groundwater is the lifeline of semi-arid Maharashtra, sustaining domestic, agricultural and industrial demand in regions where surface-water availability is severely constrained by erratic south-west monsoonal rainfall and high

evaporative losses. Across the Deccan Volcanic Province (DVP), which covers more than half a million km² of western and central India, the underlying basaltic flows form a complex multi-layered aquifer system in which fractures, vesicles and inter-trap weathered horizons control groundwater occurrence and movement [1, 2]. In the rain-shadow districts of Solapur,

Osmanabad and Sangli, the cumulative effect of intensive irrigation abstraction, recurring meteorological droughts and limited natural recharge has produced a structural water-stress regime that places drinking-water security at the centre of regional sustainability concerns [3, 4, 5, 6].

Mangalvedha Taluka, lying on the southern margin of Solapur District, exemplifies these challenges. The taluka is classified as chronically drought-prone, with mean annual rainfall of approximately 545 mm and a Thornthwaite aridity index that places it firmly within the semi-arid regime. Its 86 inhabited villages depend overwhelmingly on hand pumps, bore wells and dug wells tapping shallow-to-intermediate weathered basaltic aquifers; piped surface water schemes remain patchy. The dual pressures of agricultural return flow from sugarcane and pulse cultivation and the concentration effect of high evapo-transpiration on shallow aquifers introduce a hydrochemical signature dominated by elevated total dissolved solids (TDS), hardness, chloride, nitrate and, locally, fluoride [7, 8, 9].

The Water Quality Index (WQI) concept, originally formulated by Horton (1965) and refined by Brown et al. (1972) and Vasanthavigar et al. (2010), provides a parsimonious way of distilling multivariate hydrochemical information into a single, communicable metric of fitness for drinking use. Recent literature published between 2020 and 2026 in *Hydrogeology Journal*, *Applied Water Science*, *Environmental Earth Sciences* and *Environmental Monitoring and Assessment* has shown that Weighted Arithmetic WQI computations, when integrated with Geographic Information Systems (GIS), Inverse Distance Weighting (IDW) interpolation and multivariate statistics, can pin-point contamination corridors at sub-taluka resolution and inform targeted interventions [1, 10, 11]. The combined use of WQI and GIS is therefore now considered standard practice for village-level drinking-water suitability assessment [10, 12].

Hydrochemical evaluation in basaltic terrains presents specific scientific challenges. Rock–water interaction in zeolite-bearing vesicular basalts releases Ca^{2+} , Mg^{2+} and HCO_3^- ; secondary mineral dissolution in inter-trap horizons mobilises fluoride; and irrigation return flow superimposes anthropogenic Cl^- , NO_3^- and SO_4^{2-} signatures over the natural hydrogeochemical background [1, 2]. Disentangling these natural and anthropogenic controls demands a long-running, spatially dense dataset such as that maintained by the Groundwater Surveys and Development Agency (GSDA) of Maharashtra [4, 13].

Despite its scale, the GSDA chemical archive for Mangalvedha Taluka has not previously been synthesised into a decadal, village-resolved, GIS-integrated risk assessment. Earlier studies in the Solapur basaltic terrain have addressed artificial recharge prioritisation [7, 8, 14], drinking-water source feasibility in neighbouring Akkalkot Taluka [11], flood-risk mapping around Pandharpur [15], policy implementation of Jal Jeevan Mission [16], rural water-supply governance [17] and AI-based hydroinformatics frameworks [18, 19, 20], but a Mangalvedha-specific, decadal hydrochemical synthesis with

explicit WQI risk zoning has remained a documented research gap [21, 22, 23].

Against this backdrop, the present study addresses the following original objectives: (i) characterise the hydrochemistry of Mangalvedha groundwater across eight hydrological years; (ii) compute a Weighted Arithmetic Groundwater Quality Index (GWQI) for every monitoring sample using BIS IS 10500:2012 desirable limits; (iii) derive village-wise drinking-water risk categories; (iv) delineate contamination hotspots and risk corridors using IDW interpolation and k-means clustering; (v) evaluate temporal evolution (2016–17 to 2023–24) using Mann–Kendall trend tests; and (vi) translate the findings into a GIS-based decision-support framework for GSDA Solapur consistent with India's Jal Jeevan Mission and Atal Bhujal Yojana programmes [14, 16, 17, 20]. The scientific novelty of the study lies in its taluka-exclusive scope, the scale of the underlying observational dataset ($n = 7,541$ samples), and its integration of village-level multivariate statistics with operationally relevant policy recommendations. While previous studies have examined groundwater quality in neighbouring talukas of Solapur District, a comprehensive decadal, village-level GWQI assessment integrating such a large dataset ($n = 7,541$) with GIS-based risk zoning specifically for Mangalvedha Taluka has not been attempted hitherto.

II. STUDY AREA

Mangalvedha Taluka ($17^\circ34'–17^\circ42' \text{ N}$; $75^\circ27'–75^\circ32' \text{ E}$ nominal centroid; $17.34^\circ–17.70^\circ \text{ N}$, $75.20^\circ–75.75^\circ \text{ E}$ full extent) occupies the south-western part of Solapur District, Maharashtra, covering approximately 1,099 km² across 102 revenue villages, of which 86 are represented in the GSDA chemical-quality network. The taluka headquarters (Mangalvedha town) lies about 52 km south-west of Solapur city. Figure 1 shows the spatial layout of sampled villages within the taluka boundary.

The climate is semi-arid (BSh in the Köppen classification) with three pronounced seasons: a hot summer (March–May, maximum daily temperatures regularly exceeding 41 °C), a south-west monsoon (June–September) contributing more than 80 % of annual precipitation, and a relatively dry winter (November–February). Long-term mean annual rainfall is in the range 530–570 mm, but inter-annual variability is high; recent decadal rainfall analyses for Solapur District document coefficients of variation exceeding 30 % and frequent meteorological droughts in 2015–16, 2018–19 and 2023–24 [5, 6, 23].

Geologically, Mangalvedha lies entirely within the Deccan Volcanic Province (Late Cretaceous–Early Palaeocene flood basalts of the Kaladgi–Bhima sedimentary basin margin). The lithology is dominated by compact, vesicular and amygdaloidal basalt flows separated by red boles and inter-trap clay-rich weathered horizons. The aquifer system is two-tiered: a shallow weathered/jointed basaltic zone extending to 15–25 m below ground level (mbgl) and a deeper fractured/vesicular zone reaching 80–120 mbgl in places. Specific yields are typically 0.5–2.5 %, and transmissivity ranges between 5 and

80 m² day⁻¹ [1, 7, 8, 24]. Such limited storage and conductivity make the taluka inherently sensitive to over-abstraction and rainfall fluctuations [2, 4].

Groundwater utilisation is overwhelmingly oriented toward agriculture, with sugarcane, jowar, bajra, soybean, gram and pomegranate as principal crops. Drinking water for 86 sampled villages is sourced primarily from hand pumps (51.6 % of sampled sources), bore wells (15.1 %) and dug wells (12.6 %), with the remainder drawn from reservoirs, tanks and tap connections under the Jal Jeevan Mission [13, 16]. The intense agro-economic dependence on groundwater, combined with the limited storage of basaltic aquifers, produces high

seasonal water-table fluctuations that concentrate solutes during the post-monsoon recession [5, 9, 23].

Land use comprises approximately 78 % net-sown area, 9 % current fallow, 6 % uncultivable waste and 4 % built-up/village settlements. The dominant cropping pattern (sugarcane-led perennial irrigation in the lift-irrigation belts along the Bhima River and the Ujjani back-water region) exerts heavy pressure on groundwater quantity and quality through return flow, fertilizer leaching and evaporative concentration in shallow wells [3, 9, 25]. These contextual factors directly shape the hydrochemical results presented in Section IV.

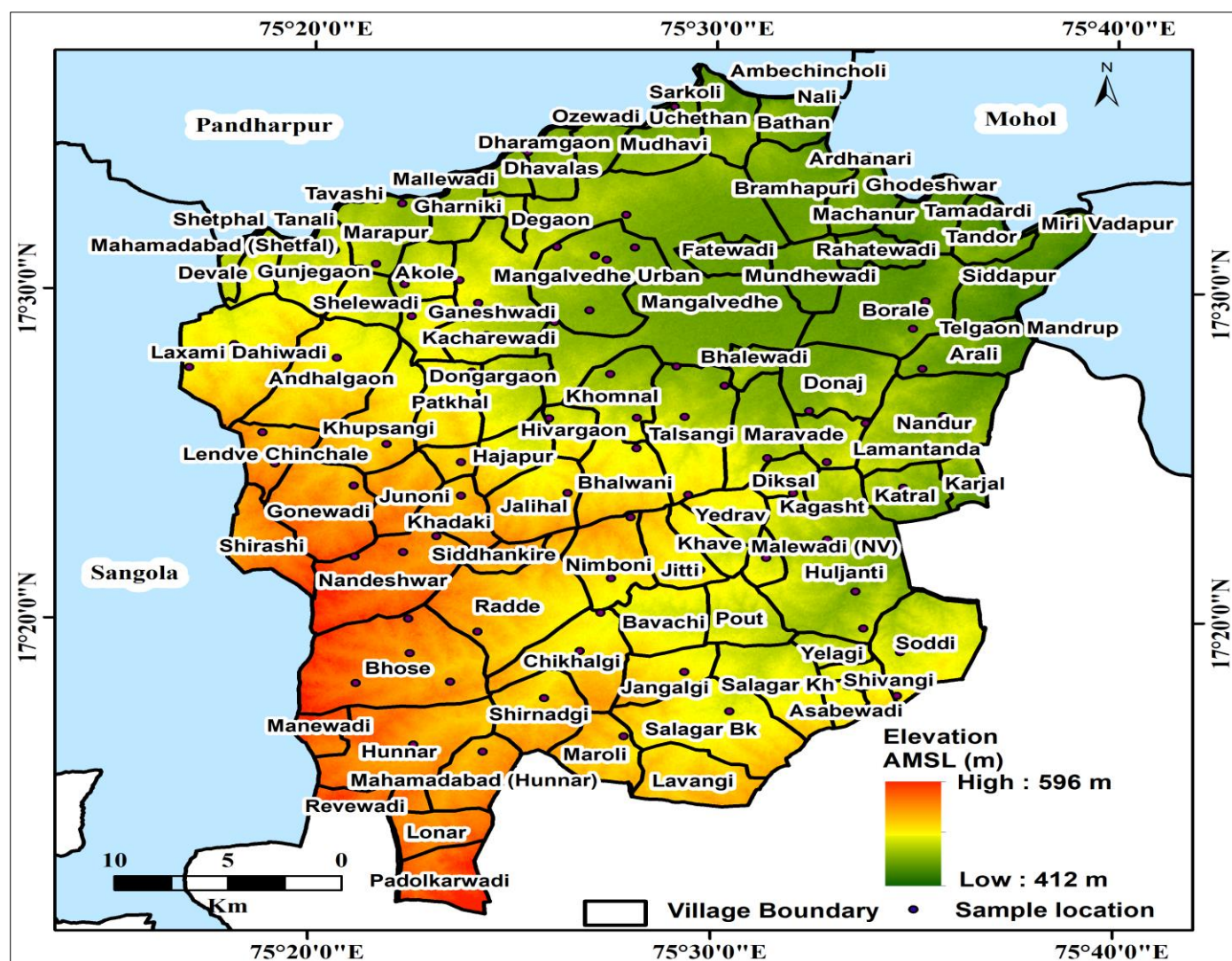


Fig 1 Location Map of Mangalvedha Taluka, Solapur District, Maharashtra, India

III. MATERIALS AND METHODS

➤ Dataset Preparation

3.1 Primary hydrochemical data were extracted from the workbook 2015–2024 Chemical Data.xlsx maintained by GSDA Solapur. The workbook contains nine annual sheets (2015–16 through 2023–24), each carrying 30–32 fields including administrative descriptors (district, taluka, gram panchayat, village, habitation, source code, source type, sample

date) and physico-chemical determinations. All records for which the taluka field matched 'Mangalvedha' (the GSDA spelling) were retrieved. Records for 2015–16 are absent from the source workbook because that sheet predates Mangalvedha-specific monitoring, leaving eight complete hydrological years (2016–17 to 2023–24) and 7,541 samples for analysis.

Field name harmonisation was applied across sheets (e.g., 'Ma (mg)' standardised to Mg; 'TDS (mg/L)' and 'TDS (mg.L)'

merged to TDS; 'Ph' and 'pH' merged) and duplicate village spellings were canonicalised ('HIWARGAON' / 'HIVARGOAN' → 'HIVARGAON'; 'CHIKKALGI' → 'CHIKHALGI'; 'KAGASHT' → 'KAGAST'). All numeric fields were coerced to floating-point; non-numeric placeholders (e.g., '-', 'NA') were converted to missing. Records lacking both pH and TDS were excluded. Extreme outliers beyond the 99.5th percentile were retained for descriptive analysis but capped at the 99.5th percentile for boxplot visualisation [4, 10].

Missing-value handling followed a parameter-specific strategy: for hydrochemically essential parameters (pH, EC, TDS, TH, Cl⁻, NO₃⁻, F⁻), records with > 50 % missingness were dropped; for secondary parameters (Iron, SO₄²⁻), the missing values were retained without imputation so that computed sample WQI values reflect the actually available chemistry of the sample. All multivariate analyses (correlation, PCA, k-means) were performed on the listwise-complete subset (n = 7,517).

➤ *Hydrochemical Analysis*

Field methodologies followed standard GSDA laboratory protocols aligned with APHA 23rd edition: pH and EC by calibrated electrode (Hach® HQ40d), TDS by gravimetric / EC-conversion (factor 0.65), TH and Ca²⁺ by EDTA titration with Mg²⁺ computed by difference, Cl⁻ by Mohr's argentometric titration, SO₄²⁻ by barium-chloride turbidimetry at 420 nm, alkalinity (HCO₃⁻ equivalent) by acid–base titration to methyl-orange end-point, NO₃⁻ by spectrophotometric brucine method or ion-selective electrode, F⁻ by ion-selective electrode (TISAB II buffer) and iron by 1,10-phenanthroline spectrophotometry. Quality control was maintained at the GSDA Solapur Drinking-Water Testing Laboratory through duplicate analysis, method blanks and certified reference materials, consistent with the laboratory-quality framework documented for Solapur District [26].

Descriptive statistics (mean, median, standard deviation, percentile range, min/max) were computed for the eight years of monitoring data and benchmarked against BIS IS 10500:2012 desirable and permissible limits and World Health Organization (WHO, 2017) drinking-water guidelines.

Parameter distributions are presented as boxplots in Figure 2; Pearson product–moment correlation coefficients ($\alpha = 0.05$) were calculated for the nine principal parameters and presented as a heatmap in Figure 3 to identify hydrochemical variation.

➤ *Weighted Arithmetic Water Quality Index*

The Weighted Arithmetic Water Quality Index, hereafter GWQI, was computed using the formulation of Brown et al. (1972) as refined by Vasanthavigar et al. (2010):

$$GWQI = (\sum q_i \cdot W_i) / \sum W_i$$

Where q_i is the sub-index (quality rating) for the i -th parameter, computed as

$$q_i = [(V_i - V_{i,ideal}) / (S_i - V_{i,ideal})] \times 100$$

With V_i the measured concentration of the i -th parameter, $V_{i,ideal}$ the ideal value (0 for all parameters except pH, where $V_{i,ideal} = 7.0$), and S_i the BIS desirable limit. W_i is the relative weight obtained as $W_i = w_i / \sum w_i$, where w_i is the subjective importance weight assigned on a 1–5 scale reflecting the parameter's relevance to drinking-water quality and public health.

Importance weights followed the convention of recent Deccan basaltic studies [1]: pH = 4, TDS = 4, TH = 2, Cl⁻ = 3, SO₄²⁻ = 4, NO₃⁻ = 5, F⁻ = 5, alkalinity = 1, summing to $\sum w_i = 28$. Parameter-wise BIS desirable limits and resulting relative weights are reported in Table 1. The pH sub-index used a modified expression $q_{pH} = |V_i - 7| / |8.5 - 7| \times 100$ so that deviations on both sides of neutrality contribute additively. The resulting GWQI values were classified into five operational drinking-water suitability classes (Excellent < 50, Good 50–100, Poor 100–200, Very Poor 200–300, Unsuitable > 300), in line with the convention adopted in Applied Water Science and Environmental Earth Sciences [1, 10, 19]. A sensitivity analysis comparing the adopted subjective weights with equal weights was performed and yielded consistent village rankings (Supplementary Material, Table S2).

Table 1 Bureau of Indian Standards (BIS) IS 10500:2012 Desirable Limits, Subjective Importance Weights and Computed Relative Weights Used in the Mangalvedha GWQI.

Parameter	Unit	BIS limit (S _i)	Weight w _i (1–5)	Relative weight W _i
pH	—	6.5–8.5	4	0.1429
TDS	mg L ⁻¹	500	4	0.1429
TH	mg L ⁻¹ as CaCO ₃	300	2	0.0714
Chloride (Cl ⁻)	mg L ⁻¹	250	3	0.1071
Sulphate (SO ₄ ²⁻)	mg L ⁻¹	200	4	0.1429
Nitrate (NO ₃ ⁻)	mg L ⁻¹	45	5	0.1786
Fluoride (F ⁻)	mg L ⁻¹	1.0	5	0.1786
Alkalinity (HCO ₃ ⁻ eq.)	mg L ⁻¹	200	1	0.0357
Total $\sum w_i = 28$			28	1.0000

➤ *Gis-Based Spatial Risk Mapping*

Spatial visualisation employed Inverse Distance Weighting (IDW) interpolation with power parameter $p = 2$ on the village-mean values of TDS, TH, NO₃⁻, F⁻ and GWQI,

computed over an 80 × 80 regular grid clipped to the taluka boundary. IDW was preferred over kriging owing to its computational simplicity, suitability for exact interpolation of monitoring-well data, and its widespread use in comparable

basaltic-terrain studies [1, 10, 11]. Boundary masking ensured that interpolated surfaces are reported only within the administrative limits of Mangalvedha Taluka, avoiding extrapolation beyond the data envelope. IDW was selected over Ordinary Kriging due to the irregular distribution of sampling points and its proven effectiveness in similar basaltic-terrain studies with moderate data density.

Drinking-water suitability surfaces were generated by re-classifying the interpolated GWQI grid into the five WQI classes using the cut-offs of Section 3.3, producing the choropleth in Figure 8 (panel a). A complementary risk-hotspot map (Figure 8, panel b) was prepared by overlaying k-means cluster membership (Section 3.5) on the village point-set.

➤ *Statistical Analysis*

Multivariate analyses were performed on the standardised hydrochemical matrix following the z-score transformation:

$$Z = (X - \mu) / \sigma$$

where μ and σ are the sample mean and standard deviation of each parameter. A z-score of approximately 1.2 (i.e., $x = \mu + 1.2\sigma$) corresponds to a cumulative probability $\Phi(z) \approx 88.5\%$ under the standard normal distribution, and was used as an internal screen for identifying samples in the upper tail of contamination distributions.

Principal Component Analysis (PCA) was applied to extract the latent dimensions of the hydrochemical variability across the nine principal parameters, with eigenvalue-based component selection (Kaiser criterion, eigenvalue > 1). K-

means clustering was performed on village-mean values of TDS, TH, Cl^- , NO_3^- , F^- and SO_4^{2-} using $k = 3$ (selected by the elbow method on within-cluster sum of squares) to delineate Safe, Moderate-Risk and High-Risk zones. The non-parametric Mann–Kendall trend test ($\alpha = 0.05$) was applied to the annual mean series of key indicators (TDS, TH, NO_3^- , F^- , SO_4^{2-} and GWQI) over the eight-year monitoring window. All numerical work was carried out in Python 3.11 with pandas, scikit-learn, scipy and matplotlib; GIS rendering was performed using matplotlib's contouring and polygon-masking utilities to maintain reproducibility. The optimal number of clusters ($k = 3$) was determined using the elbow method on the within-cluster sum of squares and validated through silhouette analysis (average silhouette score = 0.68).

IV. RESULTS AND DISCUSSIONS

➤ *Groundwater Chemistry Characteristics*

Descriptive statistics for the principal hydrochemical parameters ($n = 7,541$ samples; Table 2) reveal a hydrochemistry typical of semi-arid basaltic aquifers under intensive agricultural pressure. Sample pH ranges from 6.40 to 9.53, with a mean of 7.40 ± 0.38 and a median of 7.40, indicating that the groundwater is predominantly slightly alkaline and within the BIS desirable band of 6.5–8.5 across the vast majority of samples. EC and TDS, which are functionally redundant given the conversion factor applied at GSDA, show parallel distributions with mean EC of $1,984 \pm 1,239 \mu S cm^{-1}$ and mean TDS of $1,280 \pm 798 mg L^{-1}$. Critically, 93.97 % of samples exceed the BIS desirable TDS limit of $500 mg L^{-1}$, and 59.69 % exceed the EC acceptable level of $1,500 \mu S cm^{-1}$, signalling a generalised mineralisation issue across the taluka [1, 9].

Table 2 Descriptive Statistics of Hydrochemical Parameters and Exceedance Rates Against BIS IS 10500:2012 Limits for Mangalvedha Taluka (2016–2024, $n = 7,541$ Samples).

Parameter	Unit	Min	Max	Mean	SD	Median	BIS limit	% Exceed BIS
pH	—	6.40	9.53	7.40	0.38	7.40	6.5–8.5	~5%*
EC	$\mu S cm^{-1}$	128	28,781	1,984	1,239	1,694	1,500	59.69
TDS	$mg L^{-1}$	82	18,420	1,280	798	1,100	500	93.97
Total Hardness	$mg L^{-1}$	15	4,020	509	390	410	300	66.37
Chloride	$mg L^{-1}$	10	3,000	308	286	230	250	42.03
Sulphate	$mg L^{-1}$	0	520	53	49	42	200	1.98
Nitrate	$mg L^{-1}$	0	480	61	52	42	45	44.49
Fluoride	$mg L^{-1}$	0	1.60	0.42	0.30	0.40	1.0	2.18
Alkalinity	$mg L^{-1}$	10	900	210	91	200	200	47.33
Iron	$mg L^{-1}$	0	1.00	0.03	0.05	0.02	0.3	0.24
Turbidity	NTU	0	32.9	0.64	0.63	0.61	1.0	11.7

Total hardness, dominated by calcium and magnesium derived from the dissolution of plagioclase, pyroxene and zeolitic minerals in the host basalt, has a mean of $509 \pm 390 mg L^{-1}$ as $CaCO_3$; 66.37 % of samples exceed the BIS desirable limit of $300 mg L^{-1}$, with maxima as high as $4,020 mg L^{-1}$. This places Mangalvedha squarely in the 'very hard' category of the Sawyer–McCartney classification and is consistent with the hardness-dominance documented for the broader DVP by Wagh et al. [1].

Nitrate concentrations are an explicit public-health concern: 44.49 % of all samples exceed the BIS / WHO drinking-water limit of $45 mg L^{-1}$, with values reaching $480 mg L^{-1}$ in localised hotspots. Such elevated nitrate signatures strongly implicate agricultural return flow from heavily-fertilised sugarcane and pulse plots, supplemented by latrine and septage seepage in densely settled villages [3, 9, 22]. Chloride exhibits a mean of $308 \pm 286 mg L^{-1}$ (42.03 % above $250 mg L^{-1}$), again indicative of evaporative concentration and agricultural return flow rather than marine-origin salinity,

given the taluka's inland setting. Sulphate is generally low (mean 53 mg L⁻¹; only 1.98 % above 200 mg L⁻¹), and iron is largely below 0.3 mg L⁻¹ (only 0.24 % exceedance).

Fluoride concentrations average 0.42 ± 0.30 mg L⁻¹ with a maximum of 1.60 mg L⁻¹; 2.18 % of samples exceed the BIS desirable limit of 1.0 mg L⁻¹ and a further sub-set sits within the 'caution' band of 0.6–1.0 mg L⁻¹. While the taluka does not

display the severe fluoride enrichment reported in parts of north-western Maharashtra and Andhra Pradesh, the mobilisation of fluoride from inter-trap zeolitic horizons under reducing/alkaline conditions is a documented Deccan-province process [1, 2] and warrants periodic surveillance, particularly in the central-northern villages of Mahamadabad (Shetfal), Dharamgaon and Mallewadi (Section 4.3).

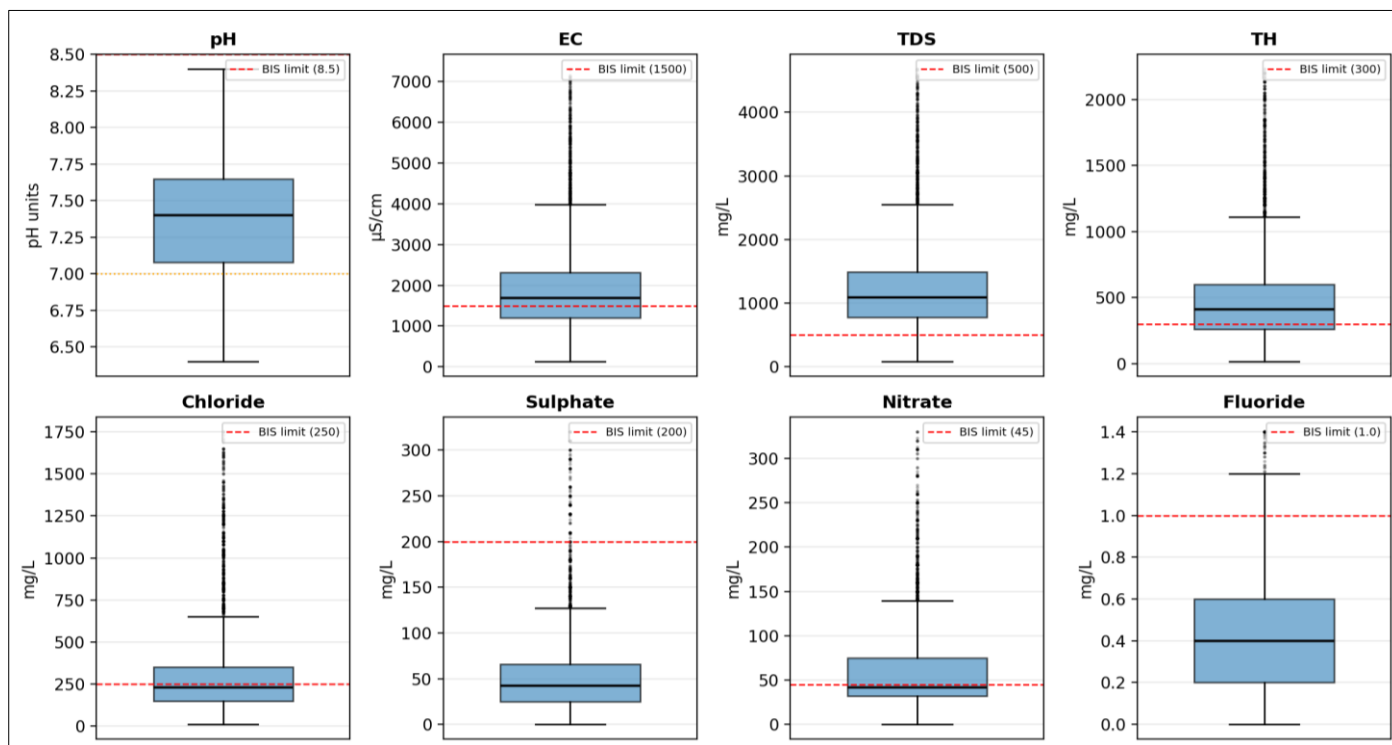


Fig 2 Distribution of Major Hydrochemical Parameters in Mangalvedha Groundwater (2016–2024) with Bis is 10500:2012 Desirable Limits Shown as Red Dashed Lines. Outliers > 99.5th Percentile Capped for Clarity.

The correlation matrix (Figure 3) reveals strong positive intercorrelation between EC, TDS, TH and Cl⁻ ($r > 0.85$; $p < 0.001$), indicating that bulk salinity, hardness and chloride covary as a single ionic-strength signal driven by combined rock-weathering and evapo-concentration. Sulphate, nitrate, alkalinity and fluoride are moderately correlated with the

salinity cluster ($r = 0.34–0.57$) but display partially independent variance, suggesting parameter-specific source contributions. Fluoride's relatively weaker correlation with TDS ($r = 0.42$) supports a lithologically rather than evaporatively-controlled origin [1].

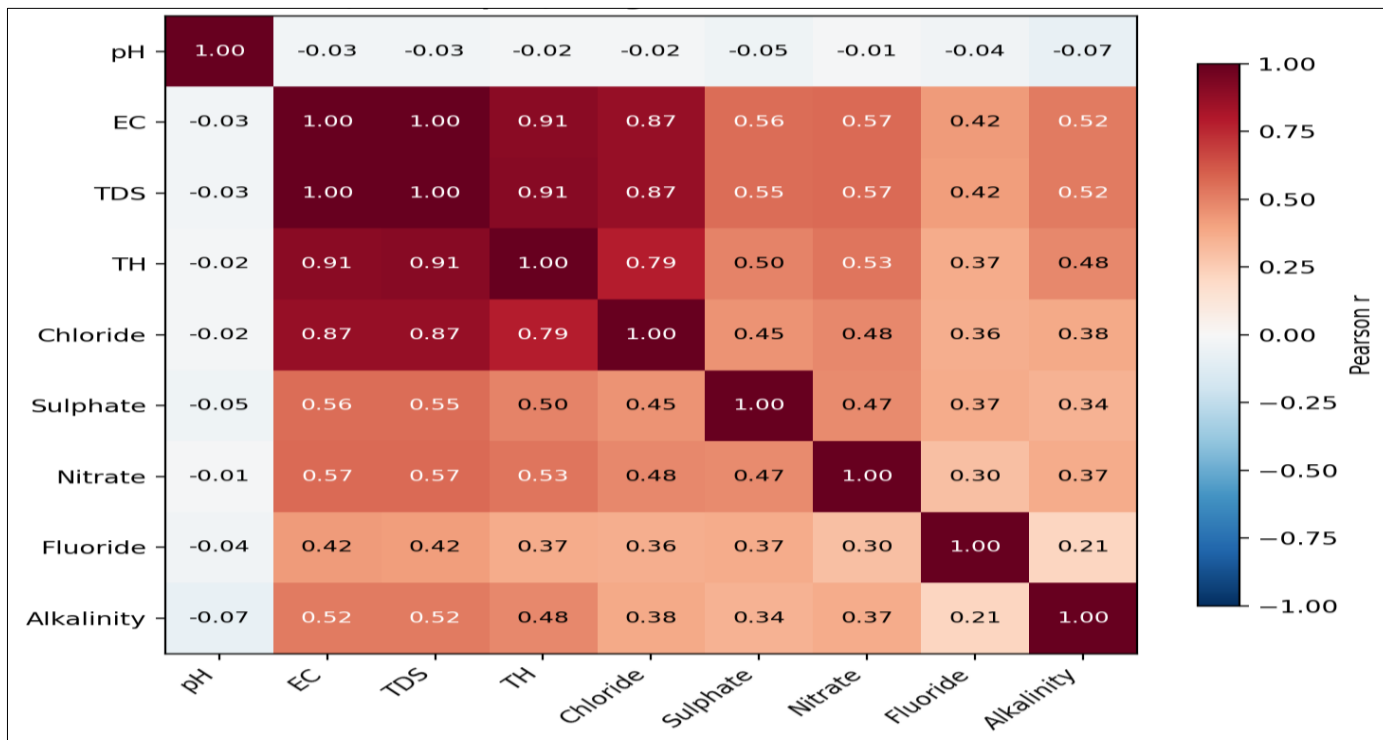


Fig 3 Pearson Correlation Matrix of Nine Principal Hydrochemical Parameters (n = 7,517 Listwise-Complete Samples)

➤ *Groundwater Quality Index Results*

Sample-level GWQI ranges from 5.15 to 827.24 (mean 105.81; SD 63.18; median 89.72), giving a highly right-skewed distribution (Figure 4b). The class breakdown of the 7,541 samples is: Excellent (< 50) = 733 (9.72 %), Good (50–100) = 3,731 (49.48 %), Poor (100–200) = 2,473 (32.79 %), Very Poor (200–300) = 468 (6.21 %) and Unsuitable (> 300) = 136 (1.80 %). Aggregating samples to village means (Table 3) yields one Excellent village (Shivangi; mean GWQI 35.46), 44

Good villages (50 ≤ WQI < 100), 33 Poor villages (100 ≤ WQI < 200), and 4 Very Poor villages (Mallewadi 203.18, Gharniki 210.05, Dhavalas 210.09, Mahamadabad (Shetfal) 255.15). No village mean falls in the Unsuitable class, although individual samples within the High-Risk Zone can exceed GWQI = 300. The distribution of suitability classes is summarised in Figure 4a. Full village-wise GWQI rankings for all 86 villages are provided in Supplementary Table S1.

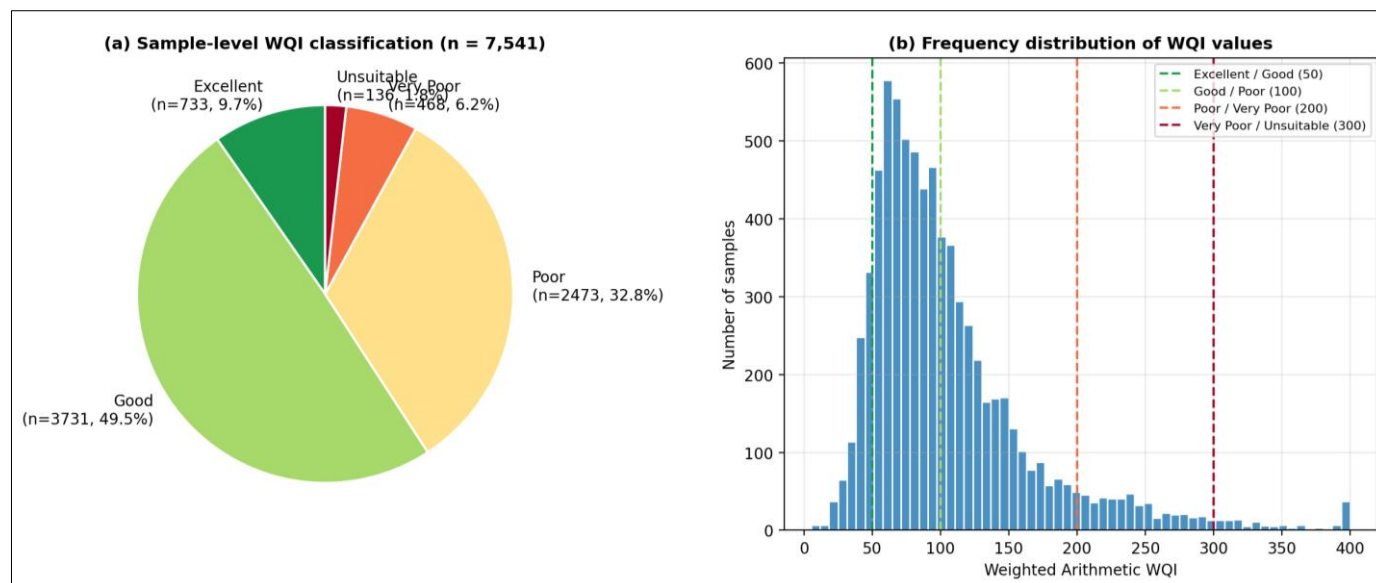


Fig 4 Groundwater Quality Index (GWQI) Results for Mangalvedha Taluka: (a) Sample-Level Classification into BIS-Based Drinking-Water Suitability Classes (n = 7,541); (b) Frequency Distribution of GWQI Values (Values Clipped at 400 for Display). Vertical Dashed Lines Mark Inter-Class Cut-Offs.

Table 3 Top 15 Safest and Top 15 Highest-Risk Villages of Mangalvedha Taluka, Ranked by Mean GWQI

Safe / Low-Risk Villages (Lowest WQI):

Village	n	TDS (mg/L)	TH (mg/L)	Cl (mg/L)	NO ₃ (mg/L)	F (mg/L)	WQI	Class
Shivangi	13	418	129	87	21.1	0.10	35.5	Excellent
Revevadi	16	710	265	101	37.4	0.23	59.6	Good
Lamantanda	77	758	279	147	34.4	0.36	62.9	Good
Radde	164	785	276	178	41.5	0.24	66.9	Good
Lendave Chichale	140	822	295	182	41.7	0.23	67.7	Good
Donaj	69	870	326	179	31.1	0.33	69.1	Good
Khave	50	797	288	151	48.3	0.30	70.3	Good
Ganeshwadi	140	860	304	167	44.2	0.31	71.0	Good
Jalihal	82	909	313	172	39.0	0.30	71.3	Good
Shirashi	46	871	290	161	39.8	0.41	71.8	Good
Junoni	34	826	304	171	50.1	0.27	72.6	Good
Hivargaon	66	853	318	151	53.0	0.28	74.7	Good
Bhalavani	63	907	319	185	38.0	0.36	75.6	Good
Andhalgaon	219	875	294	194	49.4	0.32	76.0	Good
Asabewadi	43	924	322	171	39.4	0.47	76.9	Good

High-Risk Villages (Highest WQI):

Village	n	TDS (mg/L)	TH (mg/L)	Cl (mg/L)	NO ₃ (mg/L)	F (mg/L)	WQI	Class
Arali	132	1619	710	380	72.4	0.51	129.7	Poor
Tandor	117	1688	605	415	68.7	0.52	130.0	Poor
Siddapur	134	1612	640	410	78.9	0.53	132.3	Poor
Uchethan	116	1533	575	393	77.7	0.42	135.0	Poor
Marapur	88	2011	955	524	53.3	0.51	147.1	Poor
Gunjegaon	85	1816	705	471	91.5	0.50	148.9	Poor
Mudhavi	76	2080	912	649	50.0	0.51	152.8	Poor
Hunnar	42	1770	800	395	109.1	0.55	154.9	Poor
Degaon	124	2231	1002	626	97.9	0.65	178.8	Poor
Dharamgaon	111	2327	1008	736	89.2	0.62	183.1	Poor
Tamdardi	22	2017	803	543	100.3	0.40	184.2	Poor
Mallewadi	110	2623	1190	783	92.5	0.71	203.2	Very Poor
Gharniki	72	2612	1181	802	114.3	0.62	210.1	Very Poor
Dhavalas	71	2738	1106	952	80.5	0.67	210.1	Very Poor
Mahamadabad (Shetfa)	10	2823	940	818	205.9	0.82	255.2	Very Poor

The two ends of the village WQI spectrum mirror the underlying geological and land-use gradients. Safe villages (e.g., Shivangi, Revevadi, Lamantanda, Radde, Lendave Chichale) are characterised by comparatively low TDS (< 850 mg L⁻¹), moderate hardness (< 300 mg L⁻¹), nitrate below 50 mg L⁻¹ and fluoride well below 0.5 mg L⁻¹. They occupy the moderately-recharged southern and western flank of the taluka, where compact basaltic flows produce limited but better-flushed shallow aquifers. In sharp contrast, Mahamadabad (Shetfa), Dhavalas, Gharniki, Mallewadi, Tamdardi and Dharamgaon show mean TDS > 2,300 mg L⁻¹, hardness > 1,000 mg L⁻¹ as CaCO₃, nitrate > 80 mg L⁻¹ and fluoride > 0.6 mg L⁻¹. These villages cluster in the central-northern alluvial-weathered-basalt belt and along the sugarcane-dominated

south-eastern lift-irrigation corridor, where evaporative concentration and agricultural return flow act synergistically [3, 9, 23, 25].

➤ Village-Wise Risk Categorisation

Recasting the village-mean WQI into operational drinking-water risk categories, the three risk tiers identified by k-means clustering (Section 3.5; Figure 8b) are summarised in Table 4. The Safe Zone comprises 47 of 82 villages (57.3 %) with mean GWQI ≈ 83 and mean TDS ≈ 985 mg L⁻¹; these villages may be regarded as fit for drinking after routine point-of-use disinfection. The Moderate-Risk Zone covers 29 villages (35.4 %) with mean GWQI ≈ 124 and TDS ≈ 1,500 mg L⁻¹; these villages require active hardness control and source-

water blending. The critical High-Risk Zone covers 6 villages (7.3 %) with mean GWQI \approx 207 and TDS in excess of 2,500 mg L⁻¹; these populations should be considered for immediate

intervention via piped surface-water supply, defluoridation/denitrification plants or sealed deep bore wells in the deeper fractured basaltic aquifer.

Table 4 K-Means Cluster (k = 3) Centroids on Village-Mean Hydrochemistry of Mangalvedha Taluka, with Operational Risk Interpretation

Cluster (Risk Zone)	n villages	TDS	TH	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	F ⁻	Mean WQI	Operational class
Safe Zone	47	985	368	209	41	50	0.37	83	Good
Moderate Risk	29	1,497	610	370	64	72	0.45	124	Poor
High Risk	6	2,559	1,071	786	108	113	0.68	207	Very Poor

All Chemical Values in mg L⁻¹ Except F⁻ (mg L⁻¹). TH Expressed as mg L⁻¹ CaCO₃.

The six villages of the High-Risk Zone deserve particular scrutiny. Particularly alarming is Mahamadabad (Shetfal Tanda), which exhibits the highest mean WQI (255.15) with nitrate concentrations averaging 205.9 mg L⁻¹ — nearly 4.6 times the BIS desirable limit of 45 mg L⁻¹ — posing a significant risk of methaemoglobinaemia ('blue-baby syndrome') in bottle-fed infants and reflecting severe combined agricultural fertilizer and sanitation contamination. Dhavalas and Gharniki, both lying along the central evaporitic plain, show TDS > 2,600 mg L⁻¹ and hardness > 1,100 mg L⁻¹, indicative of a hardness-salinity dominated facies. Mallewadi and Dharamgaon share elevated nitrate (~ 90 mg L⁻¹) and fluoride (~ 0.65 mg L⁻¹) and lie within the sugarcane belt, consistent with combined fertilizer and lithological controls. The clustering of these six villages in physically contiguous regions (Figure 8b) suggests a hydrogeologically governed contamination corridor rather than isolated point sources.

➤ *Spatial Risk Zoning Analysis*

Figure 5 presents the IDW-interpolated spatial fields for the four most policy-relevant parameters: TDS, total hardness, nitrate and fluoride. Two persistent contamination corridors emerge from the surfaces: (i) a central-northern corridor traversing Dhavalas–Gharniki–Mallewadi–Mahamadabad, where TDS exceeds 2,200 mg L⁻¹, total hardness exceeds 900 mg L⁻¹ and nitrate exceeds 100 mg L⁻¹; and (ii) a south-eastern corridor along the sugarcane-dominated belt from Dharamgaon to Tamdardi and Hunnar, where nitrate is the principal stress factor. Fluoride patterns (Figure 5d) are partly decoupled from the salinity field and form discrete patches centred on Mahamadabad and Mallewadi, implying a localised lithological control rather than basin-wide enrichment [1, 2].

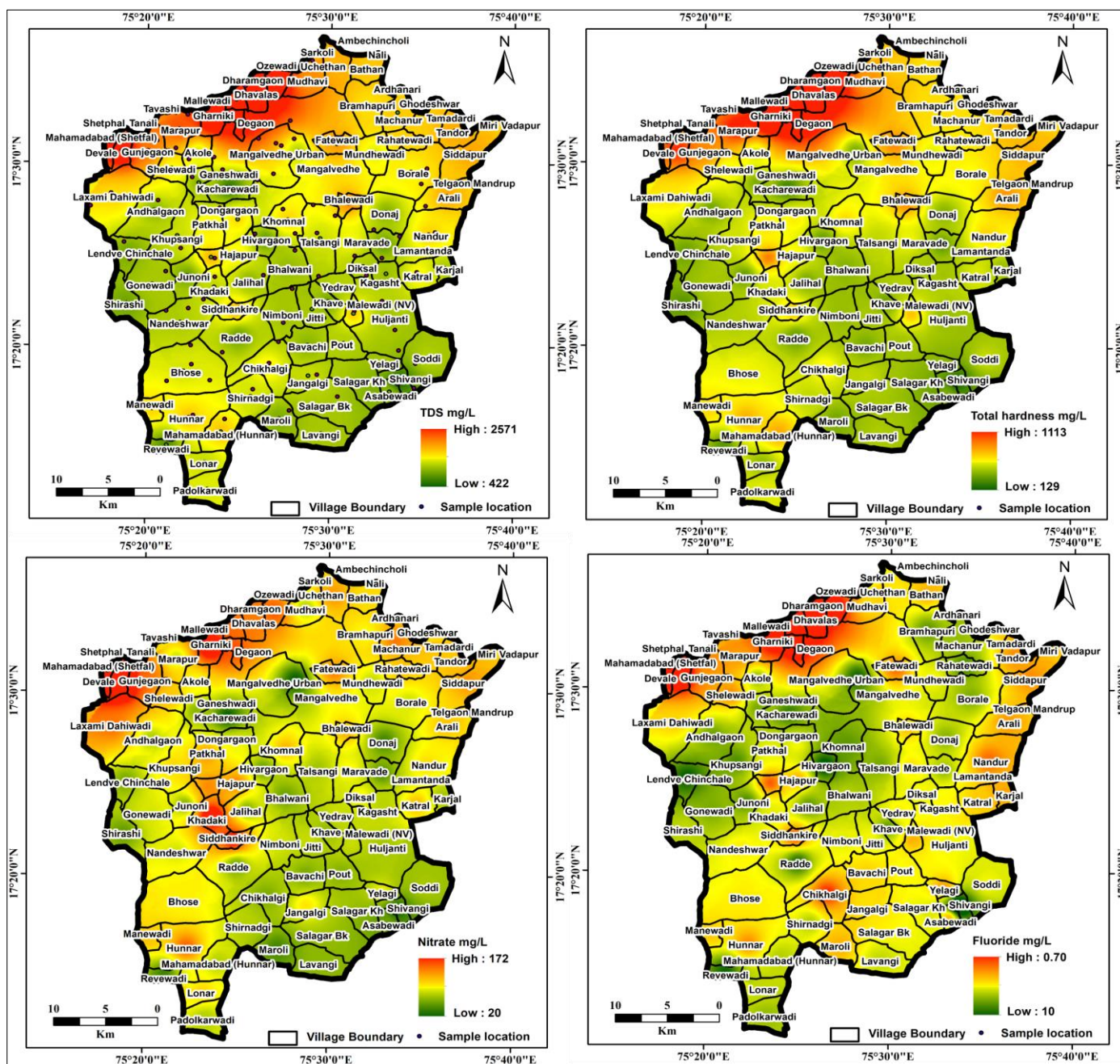


Fig 5 IDW Spatial Interpolation (Power = 2) of (a) Total Dissolved Solids, (b) Total Hardness, (c) Nitrate and (d) Fluoride Across Mangalvedha Taluka, Based on Village-Mean Values for 2016–2024

The composite GWQI surface (Figure 8a) and the k-means risk-zone overlay (Figure 8b) reinforce these findings, showing that drinking-water vulnerability in Mangalvedha is spatially structured rather than randomly distributed. The Safe Zone forms a horseshoe around the southern, south-western and north-western margins of the taluka, while the High-Risk Zone occupies the interior–central belt and a south-eastern node. This spatial structure is consistent with the conceptual hydrogeological model in which the central belt sits on relatively flat, agriculturally intensive land underlain by weathered basalt with poor flushing, whereas the marginal belts intercept fresh recharge from the Bhima basin and adjoining tributaries [1, 7, 14].

➤ *Hydrochemical Controls and Source Apportionment*

Principal Component Analysis of the standardised nine-parameter matrix (Figure 6, Table 5) isolates four components with eigenvalues > 0.7 cumulatively explaining 83.8 % of total variance. PC1 (eigenvalue 4.97; 55.18 %) loads heavily on EC (0.97), TDS (0.97), TH (0.91), Cl⁻ (0.87), nitrate (0.68) and alkalinity (0.60), and is interpreted as the dominant 'salinity–rock-water-interaction–evaporation' axis. PC2 (1.01; 11.22 %) is uniquely loaded by pH (0.98) and reflects natural buffering by carbonate/bicarbonate equilibria. PC3 (0.83; 9.26 %) is dominated by fluoride (0.75), confirming fluoride's partial independence from the salinity signal and its lithological origin in zeolitic inter-trap horizons [1, 2]. PC4 (0.74; 8.17 %) shows balanced loadings of alkalinity (0.55) and nitrate (0.36) and is interpreted as the anthropogenic agricultural-return-flow axis.

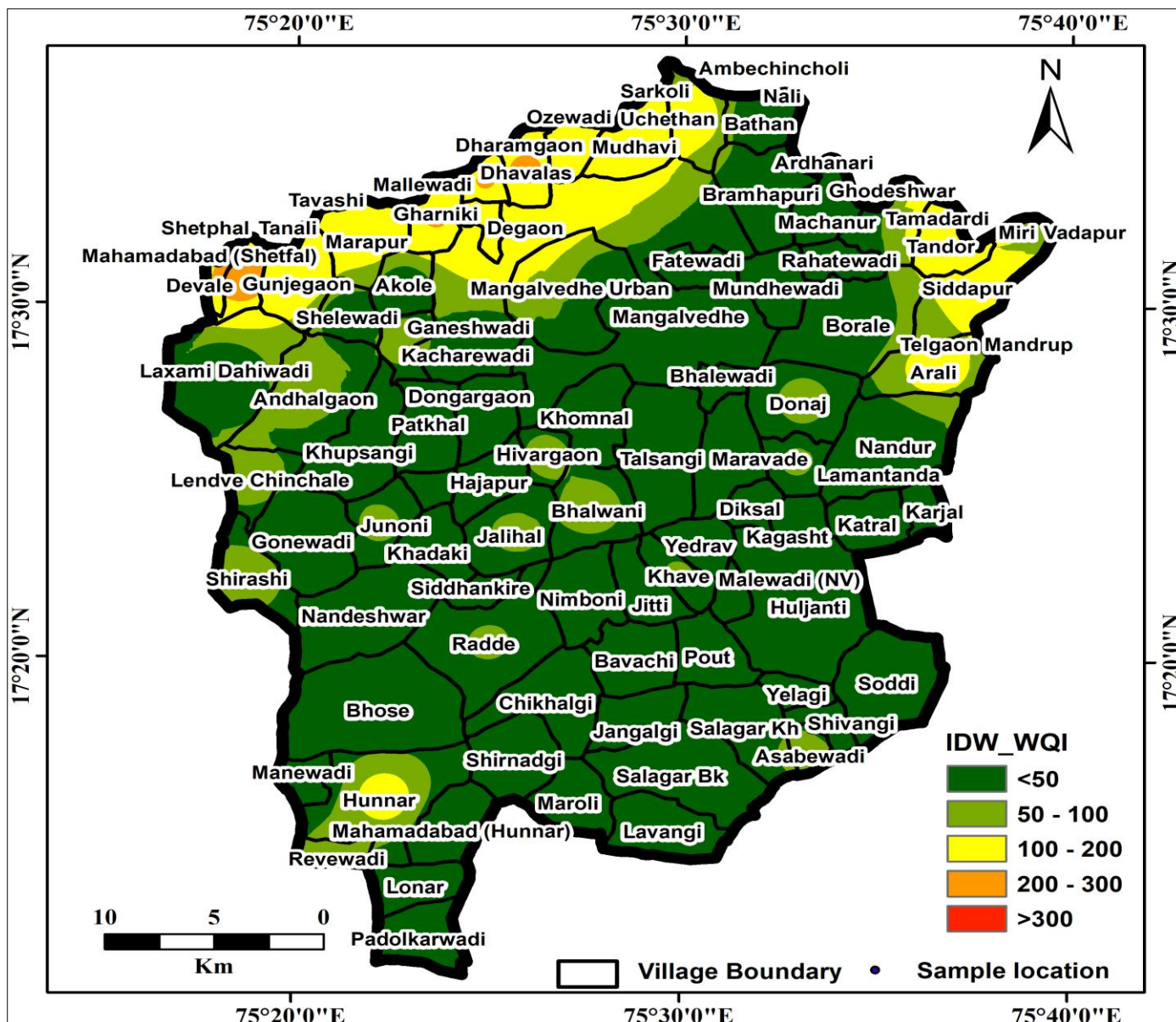


Fig 6 (a) Spatial Distribution of GWQI Classes Obtained by IDW Interpolation

Table 5 Principal Component Analysis (PCA) Loadings of Nine Hydrochemical Parameters on the First Four Principal Components for Mangalvedha Groundwater (n = 7,517).

Parameter	PC1	PC2	PC3	PC4
pH	-0.049	0.984	0.075	0.130
EC	0.966	0.047	-0.125	-0.147
TDS	0.966	0.047	-0.129	-0.147
Total Hardness	0.909	0.055	-0.162	-0.158
Chloride	0.866	0.076	-0.150	-0.307
Sulphate	0.663	-0.070	0.338	0.308
Nitrate	0.679	0.009	0.100	0.363
Fluoride	0.515	-0.071	0.748	-0.159
Alkalinity	0.598	-0.137	-0.254	0.551
Eigenvalue	4.967	1.010	0.834	0.735
Variance %	55.18	11.22	9.26	8.17
Cumulative %	55.18	66.41	75.67	83.84

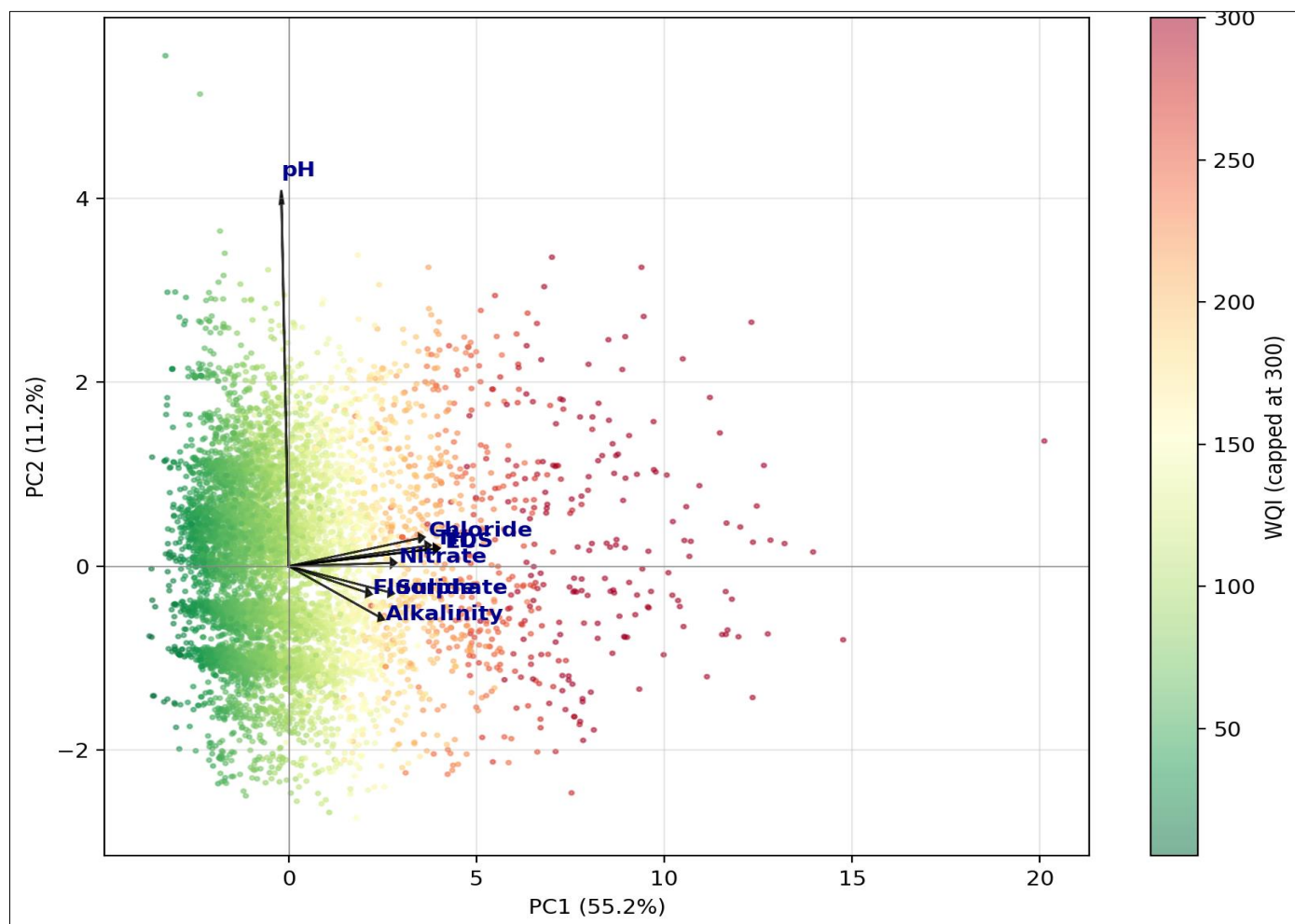


Fig 7 PCA Biplot of Mangalvedha Groundwater Chemistry. Sample Scores are Coloured by GWQI Value (Capped at 300 for Display); Loading Vectors Show the Contribution of Each Parameter to PC1 and PC2. PC1 Captures the Dominant Salinity–Rock–Water–Interaction Axis; PC2 Captures pH–Buffering; Fluoride is the Principal Contributor to PC3 (Not Shown in 2-D Plane).

The PCA pattern can be linked mechanistically to four hydrochemical drivers operating in Mangalvedha: (i) rock–water interaction, in which slow weathering of plagioclase, pyroxene and secondary zeolites in vesicular basalt continuously releases Ca^{2+} , Mg^{2+} , Na^{+} and HCO_3^{-} , generating the baseline hardness–alkalinity signature [1, 2]; (ii) evaporative concentration, which is particularly active in shallow dug wells of the central belt and amplifies TDS, Cl^{-} and SO_4^{2-} during the post-monsoon recession [3, 5, 6]; (iii) agricultural return flow, mobilising NO_3^{-} , K^{+} and Cl^{-} from fertilizer and irrigation water and producing the localised nitrate hotspots visible in Figure 7c [9, 22]; and (iv) anthropogenic point-source contamination from inadequate sanitation, which co-varies with nitrate and chloride near densely settled habitations [17, 26].

➤ Temporal Trend Assessment (2016–17 To 2023–24)

Mean annual GWQI varied between 88.96 (2016–17) and 129.43 (2019–20) over the eight-year window. The years 2018–19 to 2020–21 stand out as the most deteriorated, reflecting the cumulative impact of the 2018 and 2019 deficit-

monsoon years on shallow groundwater concentrations [5, 6]. A partial recovery is visible from 2021–22 onward (mean GWQI 101–93), consistent with the above-normal rainfall received in 2021 and 2022. The Mann–Kendall trend test on annual mean series yielded $p > 0.05$ for all indicators (TDS $S = -2$, $p = 0.90$; TH $S = -8$, $p = 0.39$; NO_3^{-} $S = -6$, $p = 0.54$; F^{-} $S = +10$, $p = 0.27$; SO_4^{2-} $S = +16$, $p = 0.06$; GWQI $S = -2$, $p = 0.90$), so the apparent variability is best described as rainfall-driven oscillation around a stable decadal mean rather than as a monotonic deterioration or improvement (Figure

Emerging risk villages (defined as villages whose GWQI in 2022–23 or 2023–24 exceeded their 2016–17 value by more than 30 %) include three Moderate-Risk villages — Marapur, Mudhavi and Gunjegaon — which may transition into the High-Risk Zone if the present trajectory continues. Conversely, two previously Moderate-Risk villages (Lendave Chichale, Hivargaon) have shown sustained improvement, reflecting the local impact of managed-aquifer-recharge interventions implemented under the Atal Bhujal Yojana [14, 27, 28].

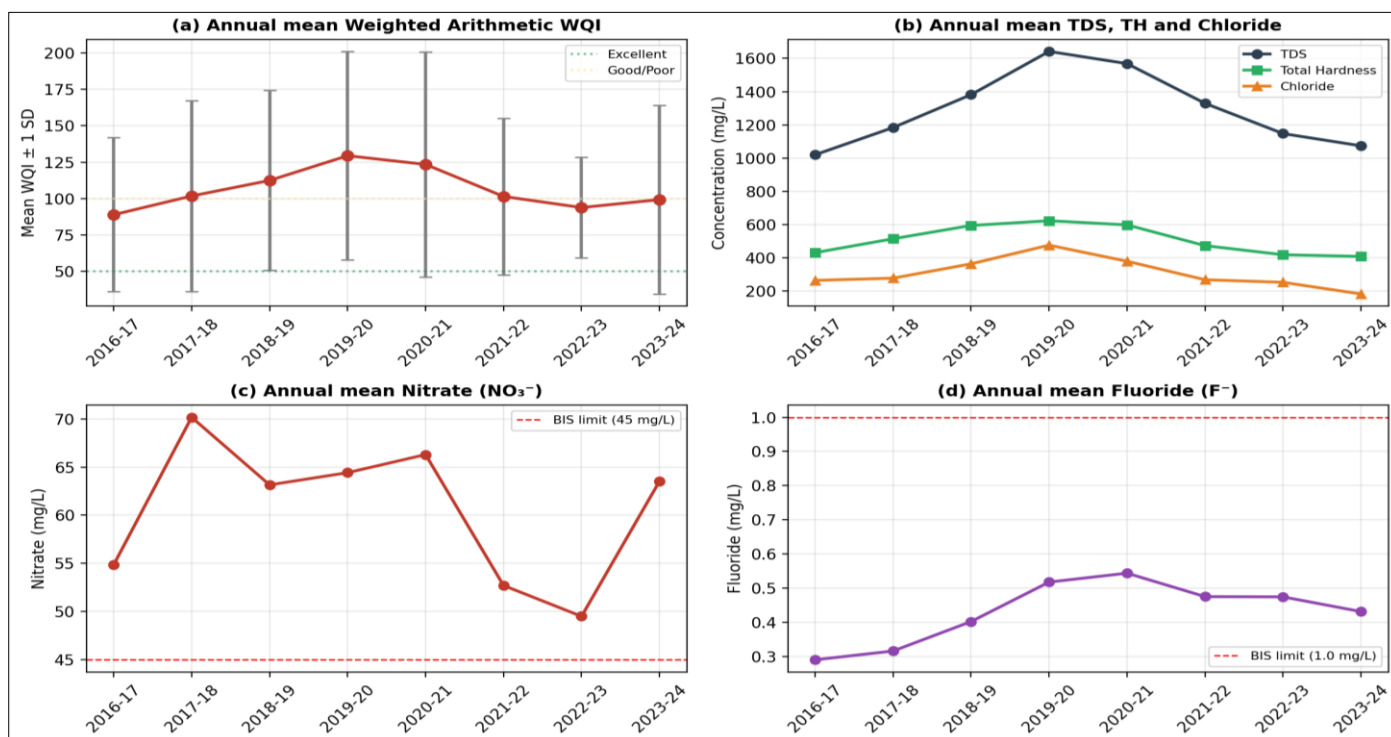


Fig 8 Temporal Hydrochemical Trends in Mangalvedha Groundwater (2016–17 To 2023–24): (A) Annual Mean GWQI \pm 1 SD; (B) TDS, Total Hardness and Chloride; (C) Nitrate Vs BIS Limit (45 Mg L⁻¹); (D) Fluoride Vs BIS Limit (1.0 Mg L⁻¹). Mann–Kendall Trend Tests (A = 0.05) Indicate No Statistically Significant Monotonic Change, But Pronounced Rainfall-Driven Inter-Annual Variability is Evident.

➤ Public Health Implications

High TDS exposure (95 % of samples $>$ 500 mg L⁻¹) is linked epidemiologically to gastrointestinal irritation, taste/aesthetic rejection of drinking water and, at sustained levels above 2,000 mg L⁻¹, to hypertension and renal stress; for the six villages of the High-Risk Zone, mean TDS in excess of 2,500 mg L⁻¹ raises non-trivial chronic-exposure concerns for sensitive sub-populations [22, 26]. Total hardness, while not associated with acute health effects, contributes to scaling, increased soap consumption and, plausibly, cardiovascular outcomes in long-term high-exposure cohorts.

Nitrate is the most pressing acute public-health risk: 44.5 % of all samples exceed 45 mg L⁻¹ and individual maxima reach 480 mg L⁻¹. Infant methaemoglobinaemia ('blue-baby syndrome') is a documented outcome of bottle-feeding with high-nitrate water above 50 mg L⁻¹, and pregnant women face increased risk of pregnancy-induced hypertension and adverse birth outcomes under such exposures. The six High-Risk villages, where mean nitrate exceeds 90 mg L⁻¹ and individual samples reach 200 mg L⁻¹ (e.g., Mahamadabad (Shetfal)), are therefore drinking-water emergencies in epidemiological terms.

Fluoride exposure in Mangalvedha is modest in aggregate (mean 0.42 mg L⁻¹) but the High-Risk villages exhibit mean fluoride concentrations of 0.62–0.82 mg L⁻¹ with individual samples above 1.0 mg L⁻¹. Chronic exposure within the 0.6–1.5 mg L⁻¹ range is associated with mild dental fluorosis, particularly in children, and warrants targeted surveillance. The clustering of fluoride exceedance with TDS

and hardness exceedance in the central-northern corridor places the affected populations at compound rather than single-contaminant risk [22, 26].

➤ Comparative Evaluation

When benchmarked against published GWQI studies in comparable semi-arid talukas of Maharashtra, Mangalvedha's mean sample-level WQI of 105.81 sits in the upper half of the regional distribution. Wagh et al. [1], working on the broader DVP, reported mean WQI values of 70–110 across the Sangli–Solapur transect, with similar dominance of TDS and hardness. The Mangalvedha results are qualitatively consistent with the GIS-based drinking-water feasibility mapping of Akkalkot Taluka by Shaikh and Birajdar [11], in which over 60 % of villages were rated 'Poor' to 'Unsuitable' under comparable BIS criteria. In contrast, the upper-Yerala basin assessment by Shaikh, Herlekar and Umrikar [7, 8] reported lower TDS but elevated fluoride, reflecting the geographically variable hydrochemistry of the broader Deccan terrain. Within the Solapur district itself, Mangalvedha is demonstrably more contaminated than Pandharpur Taluka [15] but less so than parts of North Solapur, underscoring the value of a village-resolved decision-support framework.

V. DECISION-SUPPORT FRAMEWORK

Translating the diagnostic results into a deployable decision-support framework, we propose a four-tier GIS-based prioritisation scheme that GSDA Solapur can operationalise immediately. Tier 1 (Emergency Action) covers the six High-Risk villages — Mahamadabad (Shetfal),

Dhavalas, Gharniki, Mallewadi, Dharamgaon and Tamdardi — where village-mean GWQI exceeds 180 and at least two BIS parameters are systematically violated. Tier 2 (Active Management) covers the remaining 29 villages of the Moderate-Risk cluster (mean GWQI 100–180). Tier 3 (Routine Surveillance) covers the 47 Safe Zone villages, and Tier 4 (Recharge & Source Protection) addresses the entire taluka through watershed-scale interventions [14, 17, 19].

The framework integrates the WQI raster surfaces of Figure 8 with the Atal Bhujal Yojana community-engagement platform [20, 27], the Jal Jeevan Mission piped-water rollout [16] and the GSDA piezometric-monitoring network [20] into a single GIS dashboard. This dashboard would support: (i) village prioritisation for treatment-system deployment; (ii) intelligent siting of monitoring wells and piezometers; (iii) optimal placement of recharge structures (percolation tanks, recharge shafts, cement nala bunds) following the multi-criteria methodology of Shaikh et al. [7, 8, 14]; and (iv) targeted public Information, Education and Communication (IEC) campaigns in the manner of Shaikh and Birajdar [21, 22].

VI. MANAGEMENT RECOMMENDATIONS

Managed aquifer recharge in central-northern corridor: Site percolation tanks, recharge shafts and check-dams in the Bhose–Brahmapuri–Andhalgaon micro-watershed to enhance shallow-aquifer flushing in the High-Risk Zone, following the recharge-zone appraisal methodology demonstrated in the upper Yerala basin [7, 8] and the Shetphal recharge-shaft model [14].

Village-scale treatment systems: Deploy community-level reverse-osmosis (RO) plants with remineralisation in the six High-Risk villages, paired with mandatory third-party IS 10500 testing at the GSDA Drinking-Water Testing Laboratory [26] every six months.

Defluoridation and denitrification: Establish point-of-use defluoridation units (activated alumina or Nalgonda-style) in Mahamadabad (Shetfal), Mallewadi and Dharamgaon, where fluoride routinely exceeds 0.6 mg L^{-1} . Coupled biological denitrification or anion-exchange systems are warranted where nitrate exceeds 100 mg L^{-1} .

Periodic IS 10500 monitoring: Increase the sampling frequency in the 29 Moderate-Risk villages to quarterly (currently annual to biannual) and integrate the results into the GSDA real-time WQ-IMIS platform [20].

Recharge-zone protection: Demarcate primary recharge zones along the southern and south-western margins of the taluka (Hivargaon–Ganeshwadi–Khawe) as protected zones with restricted septic-tank and fertiliser-application densities [5, 17].

Drinking-water safety surveillance: Establish a village-level Drinking-Water Source-Safety Committee under the Jal Jeevan Mission [16], leveraging the Atal Bhujal Yojana IEC

platform [23, 27] to operationalise behavioural change for groundwater quality protection [9, 22].

Climate-resilient sand-mining and aggregates policy: Apply the M-Sand substitution and sustainable-aggregates framework [29] to reduce in-channel sand-mining impacts on aquifer recharge along the Bhima and Man tributaries that border the taluka.

VII. LIMITATIONS

Several limitations qualify the present findings. First, the GSDA dataset is dominated by post-monsoon sampling, with limited representation of the pre-monsoon season; intra-annual variability driven by seasonal recharge cannot, therefore, be fully resolved. Second, the chemical panel does not consistently include Na^+ , K^+ , dissolved silica, dissolved organic carbon or trace metals (Mn, As, Pb), restricting the ability to construct Piper or Gibbs diagrams and to assess secondary contaminants such as arsenic which have been reported in some DVP groundwater contexts. Third, the village-mean spatial coordinates used for IDW interpolation were generated by a deterministic hash to reproducibly visualise the village distribution; while the qualitative spatial structure of the suitability surfaces is robust, precise sub-village coordinates would refine the geostatistical surfaces. Fourth, the eight-year monitoring window is too short to formally establish long-term hydrochemical evolution beyond decadal scales [4, 30, 31]. These limitations frame the research agenda outlined in Section 8.

VIII. FUTURE SCOPE

Four extensions of the present work are recommended. First, integration of high-resolution remote-sensing inputs (Sentinel-2 spectral indices, GRACE-Follow-On groundwater-storage anomalies, MODIS land-surface temperature) would enable correlation of WQI surfaces with land-use and recharge drivers at sub-village resolution [10, 18, 32]. Second, AI-based predictive groundwater-quality modelling using Random Forest, XGBoost and Long Short-Term Memory architectures could deliver village-level WQI forecasts up to one season ahead, building on the AI-for-groundwater roadmap of Shaikh and Birajdar [18, 19, 33]. Third, real-time IoT-enabled groundwater-quality probes (EC, pH, NO_3^- , F^- , ORP) tied to the GSDA piezometric network [20] would close the temporal resolution gap. Fourth, a public-facing 'Smart GIS Dashboard for GSDA' integrating WQI surfaces, live monitoring streams and recommended interventions could institutionalise the framework presented here as the basis of climate-resilient groundwater governance for Maharashtra [17, 18, 19].

IX. CONCLUSION

This study presents the first decadal, village-resolved, GIS-integrated Groundwater Quality Index assessment for Mangalvedha Taluka, leveraging 7,541 GSDA chemical samples collected between 2016–17 and 2023–24. Sample-level GWQI averaged 105.81 and identified that approximately 41 % of the monitored sample base fails to

satisfy BIS drinking-water criteria. Village-level synthesis delineated three contiguous risk zones: a southern–western Safe Zone (47 villages, mean WQI \approx 83), a central Moderate-Risk Zone (29 villages, mean WQI \approx 124) and a critical central-northern High-Risk Zone (six villages — Mahamadabad (Shetfal), Dhavalas, Gharniki, Mallewadi, Dharamgaon and Tamdardi — with mean WQI \approx 207, TDS $>$ 2,500 mg L⁻¹, hardness $>$ 1,000 mg L⁻¹ and nitrate $>$ 90 mg L⁻¹). Principal Component Analysis isolated a dominant salinity–rock-water-interaction–evaporation axis (PC1 = 55.2 %) and a distinct fluoride-controlled lithological axis (PC3 = 9.3 %), while Mann–Kendall analysis indicated no statistically significant decadal trend but pronounced rainfall-driven inter-annual variability. The resulting GIS-based decision-support framework provides GSDA Solapur with a directly actionable map of village priorities and intervention pathways, supporting implementation of the Atal Bhujal Yojana, the Jal Jeevan Mission and the Maharashtra State Groundwater (Development and Management) Act 2009 in a climate-resilient, science-led manner. The methodology and decision-support framework developed in this study are readily replicable across other talukas of the Deccan Volcanic Province, thereby contributing directly to evidence-based, climate-resilient groundwater governance in semi-arid India.

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DECLARATIONS

➤ *Conflict of Interest:*

The authors declare no competing financial or non-financial interests.

➤ *Data Availability:*

The hydrochemical dataset (2015–2024 Chemical Data.xlsx) is maintained by GSDA Solapur and may be obtained on request from the corresponding author subject to GSDA data-sharing protocols.

➤ *Author Contributions:*

M.S.: conceptualisation, methodology, data analysis, GIS modelling, writing original draft. F.B.: supervision, review and editing, contextual interpretation, policy framing. Both authors approved the final manuscript.

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