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GROUNDWATER QUALITY ASSESSMENT IN THE SUBURBAN LOCALITIES OF HADAPSAR, PUNE USING WQI METHODOLOGY

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ABSTRACT. Water Quality Index (WQI) approach has been utilized in this study to evaluate groundwater quality in suburban areas of Hadapsar, Pune, India. From borewells and open wells in Hadapsar and nearby area. Thirty-two groundwater samples were gathered. Physicochemical analysis revealed that calcium was the major cation, followed by magnesium, sodium, and potassium, while bicarbonate was the dominant anion. For Mg, K, electrical conductivity, total dissolved solids, some samples have been above allowable levels. 68.75% of samples were of good quality for drinking, according to WQI values, while 28.12% of samples have been of outstanding quality. Indicators of irrigation water quality, including the MH (Magnesium Hazard), SSP (Soluble Sodium Percentage), Percent Sodium (%Na), RSC (Residual Sodium Carbonate), and SAR (Sodium Adsorption Ratio), demonstrated that groundwater was suitable for irrigation with negligible risks related to sodium, salinity, and carbonate contents. This research highlights the significance of regular monitoring as well as analysis of groundwater resources in rapidly urbanizing areas to ensure sustainability and safety of drinking and irrigation purposes. These results offer important new information about pollution control methods, sustainable urban planning, and the management of water resources in Pune's expanding periphery.

Keywords: *Water samples, Water quality Index, Groundwater quality, Physicochemical analysis*

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INTRODUCTION

The life cycle on Earth depends heavily on water [1]. Clean water is must for healthier and sustainable growth of society, that leads growth and development of society [2]. Groundwater quality is an important aspect of environmental health and safety [3]. It is a significant supply of water for everyday tasks and drinking [4]. Rapid urbanization has increasingly strained groundwater resources that affect not only major metropolitan areas but also rapidly growing suburban regions [5], [6]. Infrastructural development often ignores the regulatory guidelines of local authorities [7], [8].

According to [9], the WQI is a useful tool for comprehending a region's water quality and presentation. A comprehensive evaluation of water quality, especially for everyday utilization, can be obtained by combining multiple physicochemical factors into single WQI value [9], [10]. Regular monitoring and analysis using the WQI provide important information for identifying potential health hazards, spotting pollution patterns, and enabling timely updates [11], [12]. Evaluation is essential to guaranteeing the sustainability and safety of groundwater resources in rapidly urbanizing places like Hadapsar [13], [14], [15].

Numerous recent studies have employed the Water Quality Index (WQI) approach to evaluate groundwater quality for drinking and irrigation purposes. For instance, [16] applied WQI for assessing spatial-temporal variability in groundwater quality in urban regions of China, while [17] examined drinking water risks in peri-urban India using integrated WQI and health risk models. [18] conducted a comprehensive hydro chemical and WQI-based assessment in a rapidly urbanizing area of China. Similarly, [19] and [20] evaluated groundwater suitability in Indian semi-arid zones using WQI, identifying geogenic and anthropogenic contamination sources. [21] and [22] integrated WQI with GIS to map groundwater risk zones in Iran. In African contexts, [23] and [24] analyzed WQI to understand domestic water quality issues in fast-developing urban clusters. Studies by [25] and [26] highlighted the significance of combining WQI with multivariate analysis to determine pollution hotspots and seasonal trends in groundwater. Collectively, these studies underscore the versatility of the WQI method and its growing relevance in assessing groundwater sustainability under the pressures of urbanization and changing land-use dynamics.

Hadapsar area is located in eastern region of Pune, Maharashtra. this is one such area which is experiencing rapid urban growth [17]. Traditionally, an agriculturally dominated area, Hadapsar, has undergone a drastic transformation in recent years, providing a way to residential complexes, industrial setups, and commercial zone development [27]. Concerns about how urbanization may affect groundwater quality have been raised by this quick development, which has altered environment [28], [29].

Some research has broadly carried out studies on groundwater pollution in Pune's urban and industrial areas, but there is still a lack of specific research on suburban areas, such as Hadapsar. Unchecked borehole drilling, industrial effluents, poor sewage disposal, and agricultural runoff are among the factors that play key roles in possible contamination [30], [31].

This study aims to analyze groundwater quality and key physicochemical parameters to evaluate its suitability for domestic use through the application of the Water Quality Index (WQI) methodology. The specific objectives are:

(i) To assess important physicochemical characteristics of water samples collected from various locations in Hadapsar, Pune,

(ii) To compute WQI values and classify water quality into standard categories,

(iii) To examine spatial variations in groundwater quality, and

(iv) To identify potential health hazards and likely sources of contamination.

The present study offers a focused, micro-level assessment of groundwater quality in a rapidly urbanizing suburban environment. Its findings provide important insight into the consequences of unplanned urban development on groundwater resources and highlight the need for timely, sustainable water management interventions.

RESULTS AND DISCUSSION

Physicochemical Characteristics

Physicochemical characterization of groundwater samples from study area showed that calcium (Ca) was the major cation, with the secondary presence of Mg, Na (sodium), potassium (K) in order Ca>Mg>Na>K. The sequence of prevalence for anions was HCO_3^- > SO_4^{2-} > Cl^- > CO_3^{2-}. Only one sample had calcium content above the desirable limit of 75 mg/L, though all samples remained within the permissible limit of 200 mg/L as per IS-10500 (2012). As for magnesium, the limit was 30 mg/L and was found to be above that in 7 out of 32 samples (21.88%). Sodium and potassium values fell within the normal ranges, with all potassium concentrations falling below the desirable 12 mg per L. Concentrations of bicarbonate (HCO_3^-) in the samples were usually high but still in the range allowed for drinking water. The quantities of sulfate and chloride were also intermediate; none of the samples had more than 250 mg per L of Cl^-, maximum permitted quantity. The carbonate levels in every sample were remained within the permissible limit of 200 mg per L.

The measured pH values ranged from 6.52-9.28. 24 (75.0%) of the 32 samples were alkaline (pH>7), suggesting the presence of bicarbonates and carbonates, while the rest had values close to neutral pH. EC (Electrical conductivity) values ranged among 205 and 1284 µS per cm; 5 samples (15.62%) were above the maximum threshold of 1000 µS per cm, indicating an elevated ionic concentration. About this, TDS, determined as EC × 0.64, were also above the preferable maximum of 500 mg per L in 6 samples (18.75%), providing further evidence on possible salinity hazards in these zones.

The above samples indicate that a few samples of groundwater are outside the permissible limit for drinking water purposes regarding Mg, TDS, K, EC, suggesting some local contamination or mineral enrichment. These fluctuations could require further hydrogeochemical assessment to pinpoint their origin.

Table 1. Location of sample sites along with Water Quality Parameters

Sample No.	Latitude / Longitude	pH / Chloride	Ca / Mg	CO_3 / HCO_3	Hardness / Alkalinity	Conductivity / TDS	Na / K	SO_4	WQI
1	18.497174 / 73.934576	7.04 / 9.94	44.6 / 19.1	87.8 / 106.2	189.81 / 233.38	640 / 409.6	10.44 / 6.12	34.92	54.37
2	18.487805 / 74.01365	7.76 / 8.87	27.6 / 19.6	86 / 111.5	149.36 / 234.73	1140 / 729.6	14.9 / 7.24	40.95	79.16
3	18.493754 / 73.967801	7.58 / 26.98	43.2 / 21.75	122.6 / 141.5	197.175 / 320.32	389 / 248.96	7.72 / 4.61	37.89	54.27
4	18.493744 / 73.967827	7.58 / 15.26	35.3 / 20.7	109.7 / 122.7	173.12 / 283.41	205 / 131.2	5.3 / 1.89	32.28	42.06
5	18.525787 / 73.965504	7.58 / 26.98	38.4 / 16.4	104.5 / 134.9	163.24 / 284.74	356 / 227.84	6.34 / 3.11	31.62	48.65
6	18.525842 / 73.965479	9.25 / 34.43	44.6 / 26.6	121.4 / 155.6	220.56 / 329.87	690 / 441.6	12.22 / 6.02	38.46	82.22
7	18.499294 / 73.941778	7.55 / 12.42	24.2 / 13.95	63.7 / 89.8	117.695 / 179.77	540 / 345.6	5.78 / 3.85	44.55	47.19
8	18.534004 / 73.960113	9.12 / 34.43	45 / 36.85	139.5 / 169.4	263.585 / 371.35	364 / 232.96	4.98 / 2.81	38.91	71.66
9	18.523169 / 74.046821	9.21 / 34.43	71.8 / 26.8	143.7 / 169.2	289.38 / 378.19	1284 / 821.76	15.64 / 8.37	28.08	113.83
10	18.508222 / 73.944074	7.33 / 13.49	39.4 / 29.4	102.5 / 134.8	219.04 / 281.33	620 / 396.8	10.22 / 5.85	32.19	59.81
11	18.483405 / 73.943921	9.28 / 34.43	41.2 / 20.7	108.7 / 131.9	187.87 / 289.28	1090 / 697.6	11.72 / 6.13	44.76	95.59
12	18.48217 / 74.069897	7.45 / 12.78	56.4 / 31.4	136.5 / 168.7	269.74 / 365.78	1154 / 738.56	15.26 / 8.24	41.67	92.1
13	18.471187 / 74.012055	7.88 / 11.05	49.2 / 39.2	127.4 / 153.5	283.72 / 338.15	540 / 345.6	5.68 / 1.91	31.62	67.25
14	18.470367 / 74.020537	7.28 / 5.68	57 / 32	149.5 / 176.4	273.7 / 393.76	450 / 288	6.38 / 4.73	27.96	61.72
15	18.492168 / 73.930348	7.44 / 13.49	11.4 / 11.05	58.7 / 81.3	73.805 / 164.47	1022 / 654.08	12.66 / 7.11	38.73	63.3

Sample No.	Latitude / Longitude	pH / Chloride	Ca / Mg	CO_3 / HCO_3	Hardness / Alkalinity	Conductivity / TDS	Na / K	SO_4	WQI
16	18.486715 / 73.928698	7.08 / 11.05	27 / 37.45	75.2 / 135.3	221.045 / 236.23	579 / 370.56	11.74 / 6.34	34.89	52.97
17	18.474994 / 73.931796	6.83 / 9.58	71.1 / 18.9	86.1 / 146.4	255.24 / 263.5	647 / 414.08	12.42 / 5.87	30.93	64.07
18	18.486775 / 73.928716	7.02 / 11.71	49.15 / 29.1	119.7 / 194.8	242.185 / 359.17	745 / 476.8	4.32 / 4.21	46.53	69.36
19	18.484753 / 74.020967	7.03 / 9.63	27 / 16	82.8 / 119.3	133.1 / 235.79	302 / 193.28	10.64 / 6.88	29.64	36.64
20	18.511188 / 73.937074	7.05 / 10.46	62 / 23.5	129.2 / 188.2	251.35 / 369.6	780 / 499.2	16.44 / 7.18	37.62	72.56
21	18.500888 / 73.934659	8.06 / 22.18	38.5 / 19	80.2 / 127.9	174.15 / 238.5	485 / 310.4	7.78 / 6.23	32.94	55.44
22	18.510911 / 73.937315	6.88 / 19.62	46.5 / 15	88.7 / 115.7	177.75 / 242.67	694 / 444.16	11.82 / 4.97	23.94	59.16
23	18.493237 / 73.93134	7.72 / 28.13	41 / 27	79.8 / 117.4	213.2 / 229.23	648 / 414.72	5.74 / 3.87	25.23	60.48
24	18.503082 / 73.922765	6.76 / 27.82	42 / 18.35	87.3 / 114.8	180.235 / 239.6	483 / 309.12	14.74 / 5.84	31.29	53.49
25	18.480802 / 74.023642	6.73 / 16.23	39.2 / 20.55	73.9 / 122.5	182.255 / 223.58	380 / 243.2	16.9 / 7.48	25.56	48.2
26	18.485944 / 73.951982	6.52 / 9.65	38.25 / 17.45	72.8 / 119.3	167.17 / 219.12	436 / 279.04	9.52 / 6.36	34.77	54.52
27	18.490853 / 73.949474	7.18 / 12.17	52.5 / 40.5	144.5 / 182.4	297.3 / 390.34	871 / 557.44	5.38 / 4.66	38.04	80.08
28	18.510252 / 73.934581	6.87 / 10.2	48 / 22.5	88.1 / 134.6	212.25 / 257.16	387 / 247.68	15.04 / 7.11	29.46	48.88
29	18.484477 / 73.954496	7.14 / 14.63	36 / 11	71.9 / 102.5	135.1 / 203.85	328 / 209.92	12.68 / 8.31	33.42	37.51
30	18.482676 / 73.945038	7.58 / 11.35	22.5 / 8	58.6 / 84.9	89.05 / 167.26	289 / 184.96	16.78 / 4.96	32.43	34.41
31	18.52308 / 74.047846	6.67 / 13.16	30.2 / 12	71.3 / 94.6	124.7 / 196.37	261 / 167.04	13.82 / 4.52	22.29	39.63
32	18.497815 / 73.939729	6.68 / 12.32	76 / 36	173.8 / 209.3	337.6 / 461.22	742 / 474.88	10.36 / 8.33	28.86	87.6

Water Quality Index (WQI) Assessment

Table 1 presents WQI values derived from analyzed groundwater samples. According to the classification outlined in Table 1, of the 32 samples, 9 (28.12%) exhibited a WQI of less than 50, categorizing them as "excellent" for drinking purposes. The remaining 22 samples (68.75%) had WQI values ranging from 50 to 100, which are considered "good" quality drinking water according to the WQI criteria. 1 sample (3.12%) had WQI values ranging from 100 to 200, classifying them as "poor" water. Notably, none of the samples analyzed in this study exceeded a WQI of 200, indicating the absence of "very poor," or "unsuitable" water types within research area. Together, these findings suggest that groundwater in area is generally of good drinking quality, with a notable portion of the samples displaying excellent water quality.

Table 2. Water Quality Index (WQI) Categories of Samples from the Study Area

WQI Class	WQI Category	No. of Water Samples	% of Samples
< 50	Excellent water	9	28.12%
50–100	Good water	22	68.75%
100–200	Poor water	01	3.12%
200–300	Very poor water	0	0.0%
> 300	Unsuitable for drinking use	0	0.0%

Enhanced Parameter Exceedance Analysis

Quantitative analysis of parameter exceedances reveals critical insights beyond descriptive statistics (Figure 1) 7 out of 32 samples (21.88%) had magnesium concentrations over the IS 10500:2012 acceptable limit of 30 mg/L, making it the main water quality issue that needs to be addressed right now. Electrical conductivity exceeded 1000 μS/cm in 5 samples (15.62%), while pH values exceeded 8.5 in 4 samples (12.5%). TDS values exceeded 500 mg/L in 6 samples (18.75%), indicating elevated dissolved solids concentration in these locations

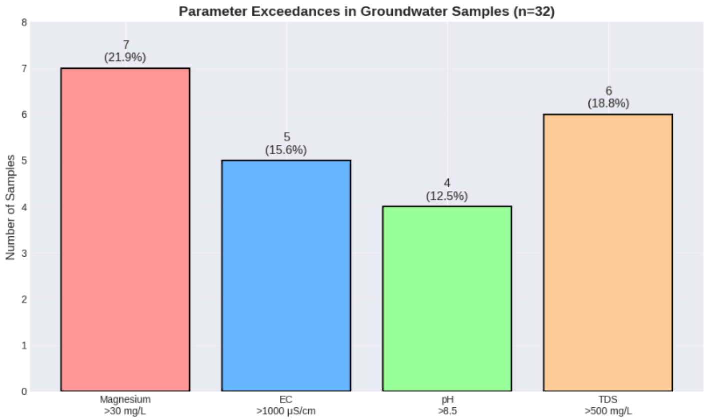

Figure 1. Parameter exceedances in groundwater samples (n=32) showing magnesium (7 samples, 21.88%), electrical conductivity (5 samples, 15.62%), pH (4 samples, 12.50%), and TDS (6 samples, 18.75%) exceeding IS 10500:2012 permissible limits

Preponderance of magnesium exceedance suggests systematic geological impacts, which are probably caused by anthropogenic inputs from farming practices or the breakdown of magnesium-bearing minerals in the Deccan Trap basalt bedrock. This finding necessitates targeted water treatment strategies focusing on magnesium removal for affected wells.

WQI Distribution and Statistical Characteristics

Detailed statistical analysis confirms that 9 samples (28.12%) exhibit excellent water quality (WQI <50), while 22 samples (68.75%) demonstrate good quality (WQI 50-100) (Figure 3). The WQI values range from 34.41 to 113.83 with a mean of 62.29 and median of 60.14.

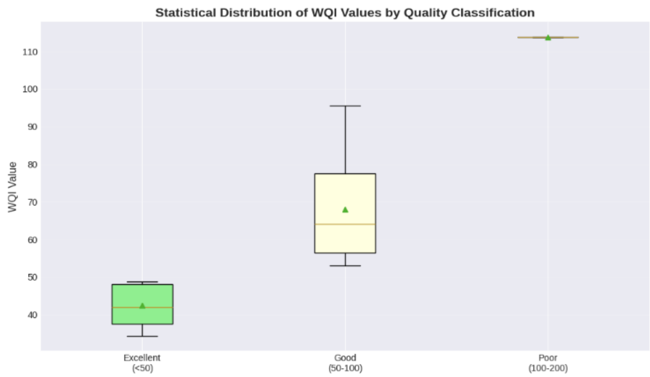

Figure 2. Box plot showing statistical distribution of WQI values across three quality categories: Excellent (n = 9, 28.12%), Good (n = 22, 68.75%), and Poor (n = 1, 3.12%) for 32 groundwater samples.

The box plot analysis (Figure 2) reveals distinct separation between excellent and good quality categories, with no intermediate values between 48-50 range. The Deccan Trap basalt bedrock's breakdown of magnesium-bearing minerals or anthropogenic inputs from farming methods are likely the causes of the prevalence of magnesium exceedance, which indicates systematic geological influences.

Hydrochemical Parameter Relationships

Correlation analysis validates key hydro chemical relationships governing water quality in research area (Figure 3). The TDS = EC x 0.64 equation used in this investigation is empirically supported by strong positive correlation among TDS and EC (r = 1.00). WQI demonstrates significant correlations with TDS (r=0.86), EC (r=0.86), magnesium content (r=0.53), establishing these as primary controlling parameters.

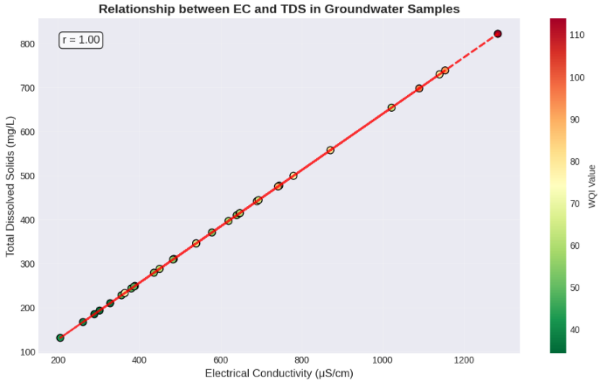

Figure 3. Scatter plot showing perfect correlation (r = 1.00) between electrical conductivity and total dissolved solids in 32 groundwater samples, with points coloured by WQI values. The red dashed line represents the regression equation TDS = EC × 0.64

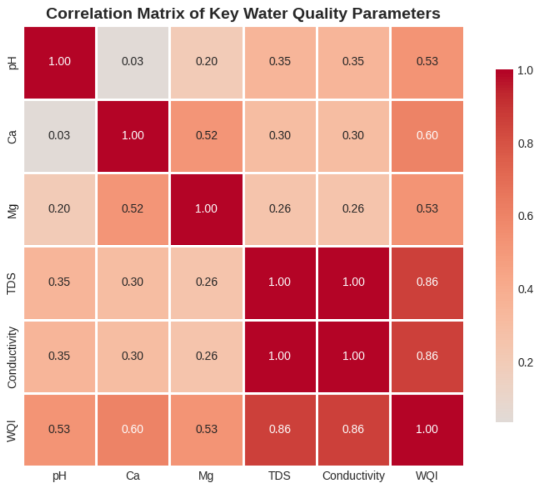

Figure 4. Correlation matrix showing relationships between water quality parameters (n=32), with notable correlations: EC-TDS (r=1.00), WQI-EC (r=0.86), WQI-TDS (r=0.86), and WQI-Mg (r=0.53).

The TDS versus EC scatter plot (Figure 4) not only validates the conversion formula but identifies potential analytical outliers requiring verification. Samples exhibiting higher WQI values consistently display elevated EC and TDS concentrations, confirming the WQI methodology's effectiveness in capturing overall water quality degradation.

Multiple Parameter Exceedance Patterns

Analysis of simultaneous parameter exceedances reveals that 37.5% of samples exceed limits for multiple parameters, suggesting systematic rather than random contamination sources (Figure 5). This pattern indicates that affected locations require comprehensive management interventions addressing multiple water quality aspects simultaneously.

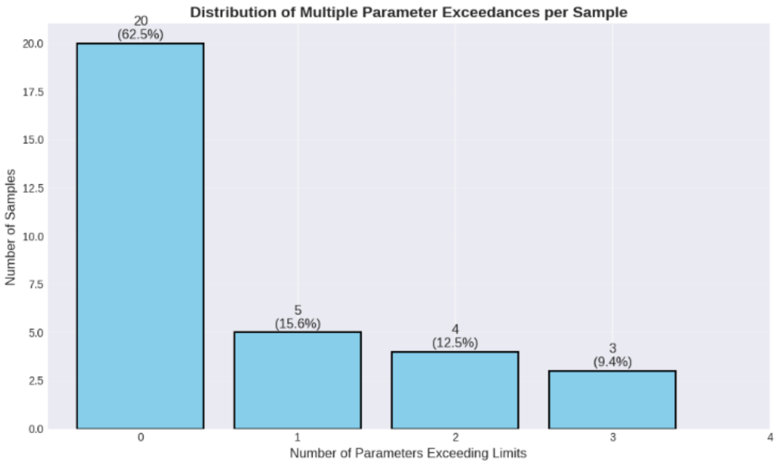

Figure 5. Distribution of samples by number of parameter exceedances showing 20 samples (62.5%) with no exceedances, 5 samples (15.6%) with one exceedance, 4 samples (12.5%) with two exceedances, and 3 samples (9.4%) with three exceedances.

The spatial clustering of multiple exceedances in specific zones supports the hypothesis that localized factors-including land use intensity, geological variations, or proximity to contamination sources-significantly effect groundwater quality across the research area.

Irrigation Water Quality Indices (IWQI)

Assessing groundwater for irrigation is particularly crucial since irrigation water may introduce soluble salts to the soil and root zone, which could negatively impact crop output and soil structure. The region's suitability for irrigation was assessed using a variety of measures, including SAR, RSC, SSP, MH, and %Na. These indices can be helpful in assessing the potential threat of high sodium and magnesium levels to soil permeability, infiltration capacity, as well as agricultural sustainability in long run. Table 3 lists obtained values of these parameters together with their interpretations in terms of general classification schemes.

Table 3. Irrigation Water Quality Indices of Hadapsar area

Sample	SAR	RSC	Na%	MH (%)	SSP (%)
1	0.33	0.87	16.67	41.39	16.81
2	0.53	1.70	25.44	53.93	25.41
3	0.24	2.46	12.69	45.36	12.66
4	0.18	2.20	8.71	49.16	8.63
5	0.22	2.43	11.86	41.32	11.75
6	0.36	2.18	15.97	49.58	15.98
7	0.23	1.24	16.01	48.73	15.99
8	0.13	2.15	6.4	57.45	6.39
9	0.40	1.77	16.02	38.10	16.07
10	0.30	1.24	14.42	55.16	14.50
11	0.37	2.03	17.83	45.31	17.97
12	0.40	1.92	16.69	47.86	16.74
13	0.15	1.08	5.8	56.78	5.72
14	0.17	2.40	8.3	48.07	8.66
15	0.64	1.81	32.62	61.51	38.22
16	0.34	0.30	14.36	69.58	15.86
17	0.34	0.17	14.12	30.47	14.14
18	0.12	2.34	7.81	49.40	7.68
19	0.40	2.05	20.56	49.42	23.42
20	0.45	2.36	17.84	38.46	17.72
21	0.26	1.28	15.94	44.86	15.87
22	0.39	1.30	17.63	34.72	17.77
23	0.17	0.32	9.53	52.06	9.49
24	0.48	1.19	20.19	41.87	20.68
25	0.54	0.82	19.34	46.36	23.46
26	0.32	1.04	18.14	42.93	18.11
27	0.14	1.85	7.56	55.98	7.35
28	0.45	0.90	19.33	43.59	19.34
29	0.47	1.37	26.29	33.50	26.55
30	0.77	1.56	32.78	36.96	35.58
31	0.54	1.43	26.52	39.58	25.02
32	0.25	2.47	10.84	43.85	11.49

Sodium Adsorption Ratio (SAR) and Other Irrigation Indices

All 32 of the groundwater samples that were examined had SAR between 0.12 and 0.77, which showed that they were completely suitable for irrigation. According to [35] , SAR values below 10 signify excellent irrigation water with a minimal sodium hazard. Consequently, all samples were classified within the 'excellent' category concerning alkali hazards. Sodium, a significant factor in soil dispersion and reduced permeability, posed no immediate risk at the observed levels.

Other irrigation quality parameters were evaluated in addition to SAR. RSC levels varied from 0.17 to 2.47 meq/L, and 29 out of 32 samples (90.6%) were within the safe limit (<2.5 meq/L), indicating minimal risk of carbonate precipitation that could affect soil structure.

The %Na values ranged from 5.8% to 32.78%, and 24 out of 32 samples (84.4%) were in excellent standard and remaining samples are suitable for irrigation in terms of sodium content. Since too much sodium can negatively affect crop health and soil permeability, all of the samples are suitable for irrigation.

According to the SSP values, which ranged from 5.72% to 38.22%, All samples were excellent and within the safe range (<40%), classifying them as ‘excellent’ for irrigation use.

However, Magnesium Hazard (MH) values indicated that 8 out of 32 samples (25%) exceeded the critical threshold of 50%, potentially contributing to adverse effects such as soil compaction and reduced aeration.

Other irrigation quality parameters were evaluated in addition to SAR. With 32 samples (100%) falling inside the safe limit (<2.5 meq per L), RSC levels varied from 0.17 to 2.47 meq per L, suggesting that there is little chance that carbonate precipitation may alter soil texture. Since too much sodium can negatively affect crop health and soil permeability, 32 samples have been deemed appropriate for irrigation, depending on %Na readings, which ranged from 5.8% to 32.78%.

According to the SSP values, which ranged from 5.72% to 38.22%., 81% of samples have been classified as ‘excellent’ for use in irrigation. Similarly, Magnesium Hazard (MH) values showed that a few samples slightly exceeded the critical limit of 50%, potentially leading to soil compaction and reduced aeration. However, the Electrical Conductivity (EC) values were within acceptable irrigation thresholds in 74% of the samples, reflecting a low salinity hazard for most samples.

Overall, the research area's groundwater showed good to exceptional quality for irrigation, with low hazards related to salinity, carbonate concentration, and sodium.

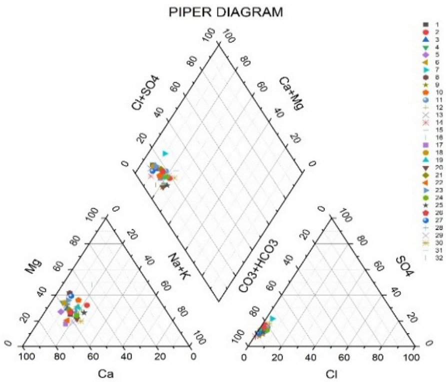

Figure 6. Piper trilinear diagram showing hydro chemical classification of 32 groundwater samples, with predominant Ca-Mg-HCO_3 water type indicating freshwater quality with temporary hardness

Hydro chemical Species Interpretation Using Piper Diagram

Hydro chemical facies in research area have been categorized, and the groundwater types were interpreted using Piper (1944) trilinear diagram (Figure 7). Five different hydro chemical facies were discovered by analyzing the geographical distribution of main anions and cations in groundwater samples: Ca–Mg–SO_4, Ca–Mg–HCO_3, Ca–Cl. 2 mixed water types were also identified: Na–Ca–HCO_3, Ca–Na–HCO_3–SO_4. Ca–Mg–HCO_3 water type was the most prevalent, indicating that majority of groundwater is of freshwater quality with temporary hardness, typically associated with shallow aquifers of recent recharge origin. These facies generally result from a dissolution of carbonate minerals involving calcite or dolomite, that occurs when infiltrating rainwater, enriched with atmospheric and soil-derived CO_2, percolates into the subsurface and chemically interacts with carbonate-bearing strata (Freeze and Cherry, 1979). The resulting reaction leads to elevated concentrations of Ca^{2+} and HCO_3^-, along with a modest increase in groundwater pH. The existence of mixed water types, including Na–Ca–HCO_3, Ca–Na–HCO_3–SO_4, indicates areas of anthropogenic influence and chemical change. These kinds might arise as a result of cation exchange activities in the aquifer system, in which groundwater's Ca, Mg are replaced by Na in soil matrix. This transformation marks a transition from pristine Ca–HCO_3 water to more evolved facies, influenced either by ion exchange or agricultural and domestic return flows. The rare presence of Ca–Cl, Ca–Mg–SO_4 types in a few samples could be attributed to localized influences involving industrial discharge, fertilization, or lithological heterogeneity, indicating some spatial variability in hydrogeochemical processes. Overall, Piper diagram confirms that groundwater chemistry in the research area predominantly reflects natural geochemical weathering of carbonate rocks, with pockets of evolving water chemistry driven by ion exchange reactions and anthropogenic activities.

Spatial Distribution Patterns

The spatial distribution of WQI values (Figure 8) reveals distinct geographical patterns in groundwater quality across the study area. Notably, samples with higher WQI values (>80) show spatial clustering, particularly in the eastern sector (longitude >74.02) and northern areas (latitude >18.51). This clustering pattern suggests localized contamination sources rather than uniform distribution, supporting the hypothesis that specific land use activities or geological variations significantly influence groundwater quality. The sample with the highest WQI (113.83) is located at the northeastern extent of the study area, while excellent quality samples (WQI <50) are predominantly found in the central and southwestern zones

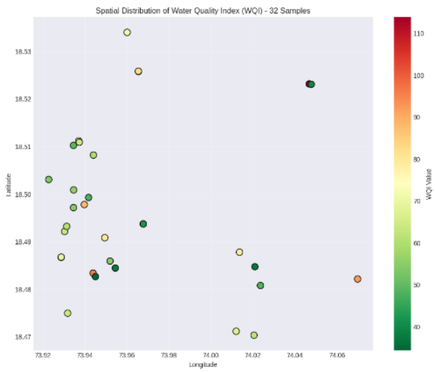

Figure 7. Spatial distribution of Water Quality Index values across 32 sampling locations in Hadapsar area. The color gradient from green (excellent quality, WQI <50) through yellow (good quality, WQI 50-100) to red (poor quality, WQI >100) reveals distinct spatial clustering, with higher WQI values concentrated in the eastern and northern portions of the study area.

This spatial pattern has important implications for targeted groundwater management strategies. The identification of contamination hotspots in the eastern and northern sectors aligns with objective (iii) of this study to examine spatial variations in groundwater quality. These findings suggest that monitoring efforts and remediation strategies should prioritize these high-WQI zones, particularly sample location 9 (WQI 113.83) in the northeastern sector. The central and southwestern zones with excellent water quality could serve as reference areas for understanding baseline conditions and may represent zones less impacted by urbanization pressures.

CONCLUSIONS

WQI methodology has been utilised to evaluate groundwater quality in Hadapsar, Pune, India, suburbs. From borewells and open wells in Hadapsar and nearby area, thirty-two groundwater samples were gathered. Physicochemical analysis revealed that calcium was the major cation, followed by magnesium, sodium, and potassium, while bicarbonate was the dominant anion. Some samples exceeded permissible limits for Mg, EC and TDS. Enhanced statistical analysis confirms that 28.12% of samples exhibit excellent quality (WQI <50) and 68.75% demonstrate good quality (WQI 50-100), with mean WQI of 62.29 indicating generally acceptable water quality with significant spatial variability. Groundwater was deemed appropriate for irrigation with low risks related to sodium, salinity, and carbonate concentrations, according to irrigation water quality indicators that included the SAR, RSC, %Na, SSP, MH.

The most significant finding is that magnesium exceedance affects 21.88% of samples, representing the primary water quality challenge requiring immediate intervention through targeted treatment strategies. Secondary concerns include EC issues in 15.62% of samples and pH exceedances in 12.50% of locations. Correlation analysis validates the analytical methodology and identifies EC, TDS, and magnesium as primary drivers of overall water quality assessment. The distinct bimodal WQI distribution indicates discrete hydrogeochemical regimes, suggesting that water quality is controlled by specific geological or anthropogenic factors rather than gradual contamination processes.

These enhanced analytical findings provide a quantitative basis for prioritising water treatment interventions and establishing monitoring protocols for sustainable groundwater management in rapidly urbanising suburban areas. The integrated geospatial-statistical approach demonstrates significant value for comprehensive water quality assessment beyond traditional physicochemical analysis alone.

EXPERIMENTAL SECTION

Materials and methods

Study area

Hadapsar is on eastern side of Pune city, Maharashtra, India, located between 18.50°N and 18.55°N latitude and 73.95°E and 74.00°E longitude. Hadapsar was once a rural territory that has evolved into a fast-paced peripheral center with high-density residential development, commercial complexes, IT parks, and upcoming industrial areas. The area experiences scorching summers, mild winters, and modest monsoon rainfall of 750 mm annually due to its tropical semi-arid environment. Hadapsar has a comparatively flat topography with scattered embankments and is lined by seasonal streams and low-lying catchments. The area falls in the upper Bhima Basin and is primarily underlain by the Deccan Trap basalt. It also hosts aquifers in weathered and fractured zones.

Groundwater is available under semi-confined conditions, mainly in fractured basalt, weathered zones, and periodic grainy patches in surface drainage. For groundwater quality variation estimation, 32 sampling locations (borewells and open wells) were chosen from Hadapsar and nearby area, representing a representative series of land use patterns from core residential to transitional fringe areas.

Sampling

Thirty-two groundwater samples were obtained from five sampling locations. The sampled specimens were referred to with site information and geographic coordinates. The samples were transferred to pre-cleaned polyethene bottles to avoid contamination. Each sample was kept in ice boxes at 4 °C until analysis to avoid any chemical modification.

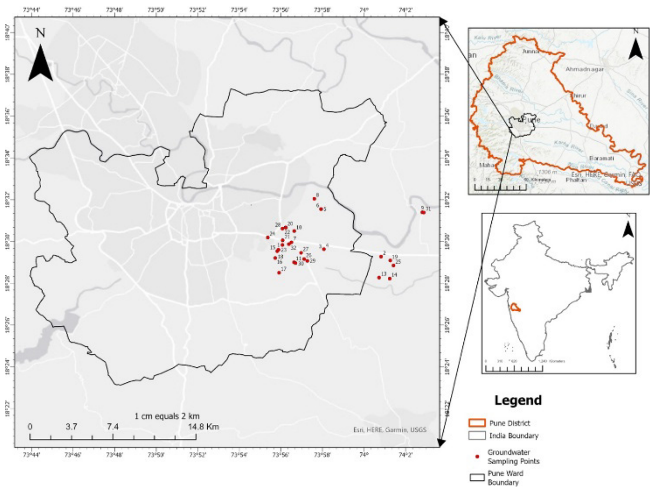

Figure 8. Location map showing groundwater sampling sites across Hadapsar, Fursungi, Manjari, and Sasane Nagar localities, Pune, Maharashtra, India. The main map displays the study area with 32 sampling locations (red dots) overlaid on Pune Ward Boundary. The upper right inset map showing regional context of Pune District within Maharashtra state, India. Lower right inset map provides national context, shows location of Maharashtra within India.

Sample collection and analysis followed Standard Methods for Examination of Water or Wastewater Guidelines of the APHA [32]. Physicochemical characteristics have also been analyzed. These involve TDS (total dissolved solids), pH, electrical conductivity (EC), Mg^{2+} (magnesium), Ca^{2+} (calcium), sodium (Na^{+}), potassium (K^{+}), carbonate (CO $^{-\ 2-}$), Cl^{-} (chloride), HCO_3^{-} (bicarbonate), sulfate (SO $^{-\ 2-}$).

Prior to each set of measurements, instruments such as pH meters, EC meters, and TDS meters were calibrated using standard buffer and conductivity solutions. Analytical precision was maintained by conducting all measurements in triplicate. Flame photometric and titrimetric analyses were validated with certified reference standards. Blank and spiked samples were incorporated as quality controls during titration to assess contamination and method accuracy. All physicochemical parameters fell within the detectable ranges of the instruments employed, and the methodology ensures the reproducibility, transparency, and reliability of the reported results.

Table 4. Overview of Analytical Techniques Employed: Parameter Assessment and Permissible WHO [33] and IS 10500:2012 [34] Limits in this Research

Parameter	**Analytical Method**	**Instrument Used**	**Reagent/Formula**	**Unit**	**WHO Standard (2017)**	**IS 10500: 2012**
pH	Electrometric Method (Direct in situ)	Digital pH Meter	-	-	6.5–8.5	6.5–8.5
Electrical Conductivity (EC)	Conductometric Method (Direct in situ)	Digital Conductivity Meter	-	μS/cm	500 (desirable)	1500 (max)
Total Dissolved Solids (TDS)	By EC × 0.64	Calculated	-	mg/L	500 (desirable)	2000 (max)
Calcium (Ca^{2+})	EDTA Titrimetric Method	Titration	EDTA-NaOH	mg/L	75 (desirable)	75–200
Magnesium (Mg^{2+})	EDTA Titrimetric Method	Titration	EDTA, NH_4OH, NH_4Cl	mg/L	30	30–100
Total Hardness	EDTA Titrimetric Method	Titration	2.5 (Ca) + 4.1 (Mg)	mg/L as $CaCO_3$	200 (desirable)	200–600
Sodium (Na^{+})	Flame Photometric Method	Systronics Flame Photometer 128	- -	mg/L	200	No guideline

Parameter	Analytical Method	Instrument Used	Reagent/Formula	Unit	WHO Standard (2017)	IS 10500: 2012
Potassium (K^+)	Flame Photometric Method	Systronics Flame Photometer - 128	-	mg/L	-	-
Chloride (Cl^-)	Argentometric Titration	Titration	$AgNO_3$	mg/L	250	250–1000
Bicarbonate (HCO_3^-)	Acid Titration	Titration		mg/L	-	-
Carbonate (CO_3^{2-})	Acid Titration	Titration		mg/L	-	-
Alkalinity	Titrimetric Method	Titration	$HCO_3^- + 2CO_3^{2-} + OH^- - H^+$	mg/L	200 (desirable)	200–600
Sulfate (SO_4^{2-})	Spectrometric Method	UV-1800 spectrophotometer (Shimadzu)		mg/L	250	200–400

Water quality index (WQI)

WQI is widely utilized technique that provides single score that indicates the water's overall quality. WQI is useful indication of water quality for range of applications, including irrigation, drinking, as well as residential water suitability. In current research, WQI has been calculated following recommendations of the Indian Standard IS10500 (2012). The analysis used the weighted arithmetic index approach, which assigns higher weights to parameters that have more serious health implications. Weights wi assigned to every parameter are inverse of their standard allowable tolerances.

The WQI was determined using the following water quality parameters provided in (Table 4). WQI has been determined using equation below:

$$WQI = \sum_{i=1}^{n} \mathrm{Wi\ qi}$$

Where: qi=quality rating of the ith parameter, wi=unit weight of parameter i , Unit weight (Wi) of every parameter has been calculated as Wi=k/Si Where: Si=standard permissible value of the ith parameter, k=proportionality constant (k=1/Σ(1/Si)).

Quality rating (qi) is expressed as qi= (Va − Vi)/ (Si − Vi) ×100. where Si is the standard acceptable limit as per IS:10500 (2012), Va is actual concentration of the parameter as determined by analysis, and Vi is ideal value (zero for most parameters, except pH, which is seven).

Table 5. Assigned Weights (wi) and Standard Limits (Si) for Water Quality Index Calculation

Parameter	Standard Limit (Si)	Assigned Weight (wi)	Relative Weight (Wi = wi /31)
pH	6.5–8.5	4	0.129
Calcium (Ca)	75 mg/L	2	0.065
Magnesium (Mg)	50 mg/L	1	0.032
Hardness	300 mg/L	3	0.097
CO3	200 mg/L	2	0.065
HCO3	200 mg/L	1	0.032
Alkalinity	200 mg/L	3	0.097
Chloride	250 mg/L	3	0.097
TDS	500 mg/L	5	0.161
EC	500 µS/cm	4	0.129
Sodium (Na)	200 mg/L	2	0.065
Sulphate	250 mg/L	4	0.129
Total		34	1

Suitability of Groundwater for Irrigation: To determine if groundwater is suitable for irrigation, several indices were computed. We computed the SAR, %Na, RSC, SSP, MH. Both indices show how soil permeability and plant health are affected by quantities of sodium, calcium, carbonate, magnesium, bicarbonate. The required input parameters were determined from the values obtained by measuring the Na+, Ca2+, Mg2+, CO32-, HCO3-, EC, TDS, and total hardness. Table 6 provides a summary of the formulas for these irrigation indices.

Table 6. The equations and classification standards applied for calculating the irrigation water quality indices.

Index	Formula	Parameters Used	Acceptable Limit	Reference
Sodium Adsorption Ratio (SAR)	SAR $=Na^{+}/\sqrt{(Ca^{2+}+Mg^{2+})/2}$	Na^{+}, Ca^{2+}, Mg^{2+}	<10: Excellent; 10–18: Good; 18–26: Doubtful; >26: Unsuitable	[35]
Soluble Sodium Percentage (SSP)	SSP $= (Na^{+} \times 100) / (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})$	Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}	<50%: Safe; >60%: Unsuitable	[36]
Residual Sodium Carbonate (RSC)	RSC $= (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$	CO_3^{2-}, HCO_3^{-}, Ca^{2+}, Mg^{2+}	<1.25: Safe; 1.25–2.5: Marginal; >2.5: Unsuitable	[37]
Magnesium Hazard (MH)	MH $= (Mg^{2+}\times100) / (Ca^{2+} + Mg^{2+})$	Mg^{2+}, Ca^{2+}	<50%: Suitable; >50%: Unsuitable	[38]
Percent Sodium (%Na)	%Na $= (Na^{+}+ K^{+}) \times 100 / (Ca^{2+}+Mg^{2+}+ Na^{+}+K^{+})$	Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}	<60%: Suitable; >60%: Unsuitable	[36]

Geospatial and Statistical Analysis

To complement traditional physicochemical analysis, geospatial and statistical methods were employed. Sampling locations (n=32) were georeferenced and mapped in ArcGIS Pro to evaluate spatial distribution and network adequacy. Statistical analyses included descriptive metrics, correlation matrices, and exceedance quantification. Data visualization using Python (matplotlib, seaborn) facilitated interpretation of spatial variability, parameter interactions, and exceedance severity, enhancing the WQI-based assessment.

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