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GIS BASED GROUND WATER ASSESSMENT OF NILAKKOTTAI TALUK, TAMIL NADU, INDIA: HYDROGEOCHEMISTRY AND STATISTICAL PERSPECTIVE

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Highlights:

- ArcGIS Pro, QGIS, SPSS and Aqua Chem software programs used in this study;
- index based irrigation water quality assessed the suitability of water samples for agricultural use;
- water quality is evaluated by physicochemical parameters, water quality indices supported by GIS techniques, multivariate modelling and hydofacies diagrams;
- outcome of the research has given better insight on the nature of ground water in the study area.

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Abstract. Water quality is imperative for drinking and agriculture purposes in order to meet the increasing requirements for water. The systematic assessment of groundwater quality in Nilakkottai Taluk, Dindigul District, Tamil Nadu, was performed. In order to ascertain the quality of the study area's groundwater, various water quality indices, spatial distribution maps, multivariate statistical analysis, and hydrofacies diagrams have been contemplated. 40 samples were collected and analysed for 20 water quality parameters, using the standard techniques. The quality results of the irrigation analysis showed that the groundwater samples were satisfactory for agricultural use. The deduction of four principal components denotes that hydrogeochemical processes and anthropogenic inputs were the main controlling factors. The durov plot demonstrated the dominance of Ca-HCO_3 type groundwater, indicating a weathering process through fresh water recharge. This study insisted that majority of the samples satisfactory for crop yield and need to be protected from further contamination.

Keywords: WQI, GIS, PCA, CA, Durov.

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1. Introduction

Water is a ubiquitous resource that is widely available and is necessary for drinking and household purposes. One of the most reliable and necessary sources of drinking water is groundwater because it is naturally occurring, easily accessible, and less susceptible to water contamination than freshwater (Todd & Mays, 2005; Wagh et al., 2016; Varade et al., 2018). According to Adimalla (2020), the groundwater quality is severely affected by certain factors, such as the effluents released from industries, agricultural fields, household activities, low rainfall, the dumpling of solid waste, and the percolation of contaminants. Human activities that release pollutants into the groundwater also have some impact on it (Amrani et al., 2020; Kadaoui et al., 2019; Zakaria et al., 2021). Therefore, it is necessary to assess the relationship between hydrogeochemistry and the source of contamination in order to protect water resources and ensure effective management. Singh et al. (2017) reported that about 14% of India's GDP comes from the agricultural sector, which emphasizes the importance of high-quality water for irrigation. Globally, numerous studies have been carried out to monitor and evaluate water quality for domestic drinking and agriculture purposes (Sarala Thambavani & Uma Mageswari, 2014; Thilagavathi et al., 2017; Zahedi, 2017; Panda et al., 2018; Xing et al., 2018; Abbasnia et al., 2018; Umamageswari et al., 2019; Gharbi et al., 2019; Umamageswari, 2022). In addition to affecting quality, groundwater contamination poses a risk to societal wealth, economic growth, and human health (Gupta, 2020; Roy et al., 2018). Therefore, it is essential to regularly check the quality of the groundwater and develop strategies and tactics to protect it (Bawoke & Anteneh, 2020).

Now a days, the quality of groundwater has deteriorated due to human activities that constitute a major risk to human health, including the uncontrolled leaching of landfill leachate, excessive fertilizer use, and other activities (Noori et al., 2018, 2021; Egbueri et al., 2021; Maghrebi et al., 2021). According to Subba Rao et al. (2022b), the overall water quality index (OWQI) is a straightforward and efficient method for gathering data on harmful factors related to drinking water quality. Use of irrigation water quality indices is one of the finest approaches to monitor groundwater quality for agricultural applications. Numerous research has analysed the quality of the groundwater in order to determine the suitability of water samples for irrigation (Bhunia et al., 2018; Mokoena et al., 2020; Sarkar et al., 2022). Lanjwani et al. (2020) calculated Sodium Adsorption Ratio (SAR), Na%, Kelly Ratio (KR) and Permeability Index (PI) from 25 groundwater wells in Pakistan and reported that the majority of the samples were satisfactory for irrigation.

Based on a study of the literature, it is evident that to address groundwater-related problems, it is necessary to understand the chemistry of groundwater and geochemical processes of the study area. Subba Rao et al. (2022a) reported that the dominant groundwater type of rural part in Telangana, India, showed the Ca^{2+}- Mg^{2+}- HCO_3^- due to the water-soil-rock interactions. Sunitha and Reddy (2022), Dhakate et al. (2023), Din et al. (2023), Saikrishna et al. (2023) reported as Piper trilinear and Gibbs diagrams are commonly used to assess the chemical components of ground water, hydrogeochemical facies and mechanism of controlling ground water chemistry in their studies.

Furthermore, Aouissi et al. (2021), Gad et al. (2021) pointed out that the assessment of water quality relies on the collaborative use of geographic information systems (GIS) and multivariate statistical approaches. GIS is primarily utilized in geology, geoenvironment, and other disciplines to collect, analyse, and present geographical data for use in decision-making processes (Adimalla & Taloor, 2020). According to Hossain et al. (2020), a number of deterministic and statistical interpolation techniques have been developed to make it simpler to examine a region's spatial characteristics, even if it is a smaller region. These techniques include Inverse Distance Weighted (IDW), Ordinary Kriging (OK), and Empirical Bayesian Kriging (EBK). For instance, Gilbert et al. (2020) examined the distribution of groundwater in India using a combination of GIS and multivariate analysis. On the other hand, Bawoke and Anteneh (2020) appraised the groundwater suitability of the Andasa watershed using WQI and GIS techniques.

In recent years, researchers have reported that the ground water quality in southern region of Tamil Nadu. Muthusamy et al. (2023) studied the groundwater quality for drinking purposes in semi-arid regions of the southern part of India. In this study, they have recommended that advanced-level treatment is required before using water for consumption and other household purposes since the majority of the research area was contaminated. Umamageswari et al. (2019) reported that parameters such as electrical conductance, turbidity, chloride, total dissolved solids, sodium, nitrite and ammonia were found to exceed BIS desirable limits of Batlagundu block in Dindigul district and unsuitable for domestic purposes. Siva Kumar et al. (2017) studied the geology, geomorphology, soil, land use and land cover, rainfall and drainage density of Dindigul district, Tamil Nadu using Analytic Hierarchy Approach (AHP) technique. Colins Johnny and Sashikkumar (2014) studied the ground water quality of 14 wells randomly distributed in Dindigul district, Tamil Nadu. In this study, they have reported that the parameters such as pH and sulphate within the limit. Natham and Palani taluk have good and moderate range of chloride. Thennampatti and Thangammapatti villages have the high fluoride concentration (>1.5 mg/L).

The primary goal of the present study is to evaluate the hydrogeochemistry of groundwater samples in Nilakkotai Taluk, Dindigul District, Tamil Nadu, India. The villages around Nilakottai Taluk are famous for flower farming. The economy of the local population mainly depends on agriculture. Groundwater is the main source for both drinking and irrigation purposes. Through a literature survey, it was found that no significant work is done for the suitability of ground water for the agricultural purpose of the study area. The motivation to conduct the research stems from a lack of awareness, information and knowledge regarding the origin and quality of groundwater. Groundwater is a vital resource for agriculture and drinking for the local population. Several water quality indices were computed in this study to assess the water's appropriateness for irrigation uses. The findings were then analysed using geographic information systems (GIS). Furthermore, multivariate statistical analysis was used to pinpoint the contamination sources. In addition, the hydrochemical behavior and water types of the study area have been classified using a hydrofacies diagram.

2. Materials and methods

2.1. Description of the study area

The current study was carried out in Nilakkottai Taluk, which is located in Dindigul district. There were 286,591 people living in this taluk as of the 2011 census. It is situated geographically at a longitude and latitude of 77.5111E and 10.9530 N. Figure 1 shows the digital elevation model of the study area. Geology is a prime source and controlling factor of the concentration of pollutants in ground water. More than 97% of the district is covered by hard rocks. The study area consists of two main geological formations such as Charnockite rocks followed by limestone bed. These rocks are considered as potential

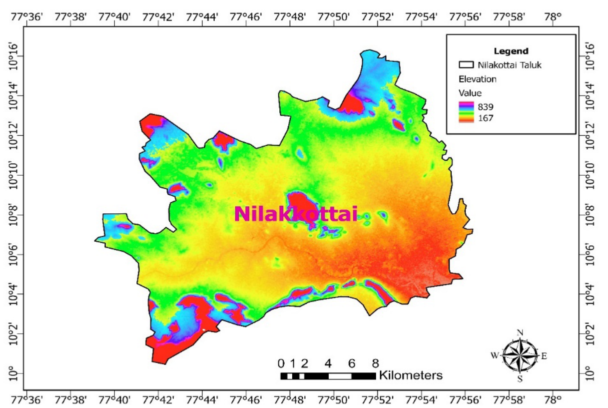

Figure 1. Digital elevation model of the study area

a) b)

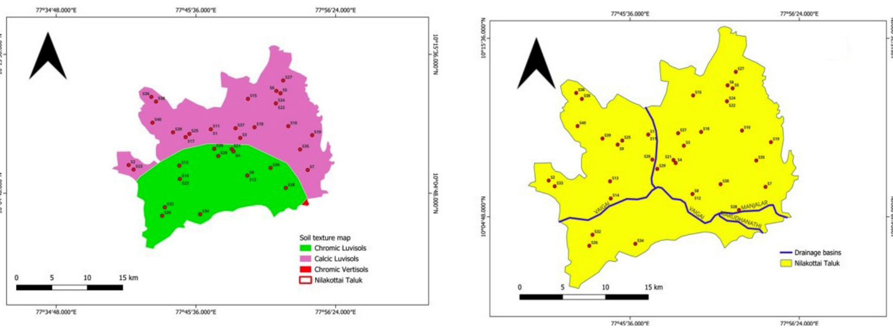

Figure 2. Soil texture and Drainage basins of the study area: a) Soil map; b) Drainage basins

aquifers which is preferred for groundwater storage. Sand, silt, clay and gravel are found in alluvial deposits along the courses of the Vaigai, Manjalar, and Marudha Nadhi rivers. The rate and depth of weathering have an impact on groundwater recharge in hard rock formations. Siva Kumar et al. (2017) reported that structural hills are found in parts of the Nillakkottai, Nattam, Vadamadurai, Oddanchatram, and Gujiliyamparai areas.

2.1.1. Soil texture and Drainage basins

Samples of the groundwater were taken at 40 distinct locations. Figure 2a displays soil texture map along with the sampling points. Soil is the most influential factor in the groundwater quality of the region. Three different soil textures are available, such as Calcic Luvisols, Chromic Luvisols, and Chromic Vertisols. Calcic Luvisols are soft powdery lime and cover 65% of the collected sampling sites. Chromic Luvisols are very deep, moderately well-drained, dark red, clayey soils covered by 35% of the collected sampling sites. None of the samples were collected from the Chromic Vertisols region.

The Vaigai subbasin encompasses the southern portion of the research area. The Manjalar, Vaigai, and Marudhanadhi rivers are significant waterways. These are equally transient in nature, receiving their flow solely during the monsoon season. A drainage basin map is displayed in Figure 2b.

2.2. Water sampling

In order to conduct the hydrochemical analysis of the study region, random sampling technique is adapted since the dug wells and bore wells are randomly found throughout the research area. In simple random sampling, suitable number of bore wells and dug wells are selected based on the population of the study area. 40 groundwater samples were collected from the study area at a distance of roughly 5 to 7 km. A total of 23 bore hole samples were taken from the shallow (<15 m depth) and deep (>15 m depth) aquifers. 17 samples taken from dug wells and varied the depth from ground level to 20 m. All the 40 groundwater samples were collected during the year 2022 in the post-monsoon period (October to December). The samples were collected using high density polyethylene bottles with a one-litre capacity. Bottles were carefully pre rinsed with distilled water and dilute HNO_3 acid (pH < 2). The samples were stored in an ice box and transported to the laboratory for the chemical analysis. All the chemicals used were AR grade of pure quality.

2.2.1. Field and laboratory analysis

Based on American Public Health Association (2005) procedures, 20 parameters were examined. The parameters such as temperature, pH and electrical conductivity were measured within the field. TDS was determined by weight and drying at 103–105 °C in the oven. Total hardness, calcium and magnesium concentration were obtained by titration method using EDTA (Ethylene Diammine Tetra Acetic acid) while chloride concentration was obtained by argentometric titration using standard silver nitrate as a reagent. The concentration of alkalinity and bicarbonate were analyzed by standard HCl titration method. Dissolved oxygen was determined by Winklers iodometric method while BOD was determined by 5 days incubation at 20 °C. COD was obtained by using acidified $K_2Cr_2O_7$.

Phosphate was determined by spectrophotometric method using acid molybdate. Nitrate determination in water sample was done by cadmium column reduction method. Fluoride was determined by SPANDS method (Sodium 2- (Parasulphophenyl Azo)-1, 8 dihydroxy – 3, 6 Naphthalene Disulphonate). Sodium and Potassium were determined by using flame photometer in the flame emission mode at a wavelength of 589 nm and 768 nm respectively.

2.3. Spacial maps and statistical analysis

Spatial distribution maps were generated by QGIS software version 3.30 using Inverse Distance Weighed (IDW) over the kriging interpolation method and estimated irrigation water quality parameters. Multivariate statistical analysis such as principal component analysis (PCA) and cluster analysis (CA) were also employed to identify the parameters that influence the water quality. In PCA, the popular orthogonal rotation method, also known as Kaiser-Varimax rotation, is used to prevent multicollinearity between model parameters. According to the Kaiser Criterion, PCs are summed for the maximum variance of more than one eigenvalue with varimax orthogonal rotation loading (Subba Rao et al., 2024). Multivariate statistical analysis were performed by SPSS software (Version-23). The hydrogeochemistry of the study area was studied by Durov plot using Aqua chem Software (Version 5.1). The findings were interpreted in light of the research area's variations in groundwater quality. The research methodology used for this study was summarized in Table 1. Extracted samples were used to assess the appropriateness for irrigation.

Table 1. Methodology adopted for the current research work

S. No	Parameters	Methodology
1	Preparation of Base map	Survey of India topographic maps of 1:50000 scale
2	Location Coordinates	Global Positioning System
3	Temperature	Mercury Thermometer
4	pH and EC	Multi parameter tester (PCS tester 35)
5	Turbidity	Digital Nephelometer (HV-34)
6	TDS	Temperature Controlled Oven
7	Total hardness, Total alkalinity, Calcium, Magnesium, Chloride, DO, BOD and COD	Digital Titrimetric method
8	Sulphate, Nitrate, Fluoride, Phosphate	UV- Vis Spectrophotometer (Shimadzu UV-1800)
9	Sodium and Potassium	Flame photometer (ELICO CL 361)
10	Fecal Coliform	Multiple tube fermentation method
11	Digital elevation model	ArcGIS Pro Version 3.1
12	Soil texture map, Drainage basins map and Spatial Distribution map	QGIS version 3.30, Inverse Distance-Weighted (IDW) interpolation method
13	Hydro facies diagram	Aquachem software Version 5.1
14	Multivariate statistical analysis	SPSS software Version-23

3. Results and discussion

3.1. Descriptive summary of the physico chemical parameters of ground water

The entire hydrochemical data of the studied samples from the research area is presented in Table 2, including mean, standard deviation (SD) and coefficient of variance (CV). The investigation and analysis reported that the temperature of all groundwater samples collected below 40 °C. The samples of ground water from S11, S15, S25, S33, and S39 recorded turbidity within the limit. High turbidity may be associated with more suspended materials and soluble organic compounds. Total alkalinity in water is due to the presence of hydroxides, carbonates, and bicarbonates. It was calculated with an average of 277.48 mg/L and was within the desirable limit of World Health Organization (WHO, 2017) standards.

The occurrence of the cations in the research area was found to be in the following order: $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$. The findings showed that both anthropogenic and geogenic inputs were typically the source of the cations in the studied area.The present findings are well correlated with Sako et al. (2018), who described that the cations were generally derived from ionic exchange reactions, silicate weathering, and orthoclase weathering in the Upper Precambrian sedimentary aquifer of northwestern Burkina. The dominance of the anions in the study area was found to be $Cl^{-} > HCO_3^{-} > SO_4^{2-} > F^{-} > NO_3^{-} > PO_4^{3-}$. Geogenic sources releases bicarbonates, sulphates and fluorides. Nitrates and phosphates mainly contributed from anthropogenic inputs such as agricultural activities. The reports of nutrient parameters such as DO, BOD, and COD of the study area were within WHO (2017) standards. Every sample within the research region met the fecal coliform count (0 cfu/ml) of WHO standards.

3.2. Water quality for irrigation purposes (WQI_{irr})

The irrigation water quality index gives a distinct classification of water quality based on the effects on plants and soil (Adimalla & Taloor, 2020; Gad et al., 2020a). In this

Table 2. Descriptive outcomes for the analysed physico chemical parameters of the study area

S S	Temp	Tur	TH	TDS	EC	pH	TA	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	F^{-}	NO_3^{-}	PO_4^{3-}	DO	BOD	COD	HCO_3^{-}
S1	22.7	2.3	130	569	326	7.2	295	54	25	119	15	162	38	0.4	3	0.98	5.4	1.2	5.1	358
S2	22.8	2.2	184	879	1048	8.3	303	55	24	321	16	159	37	0.5	3	0.87	5.6	1.3	5.6	366
S3	22.9	1.5	200	963	1029	7.6	302	69	26	118	14	145	39	0.9	3	0.95	5.5	1.1	5.9	368
S4	20.3	2.3	75	256	523	7.8	165	65	18	315	17	215	65	0.1	4	0.93	5.3	1.5	6.1	313
S5	20.2	4.8	260	648	963	7.5	332	64	19	109	18	235	69	0.1	5	0.98	5.4	1.6	5.4	317
S6	20.1	1.2	388	1023	1235	7.7	196	76	17	332	16	501	67	0.1	3	0.78	4.9	1.4	5.9	311
S7	20.7	2.9	328	769	1025	7.2	390	90	53	325	23	400	62	0.6	5	0.84	6.1	1.5	5.2	474
S8	20.6	4.8	260	698	1123	7.6	407	56	52	121	22	235	61	0.59	6	0.76	6.4	1.7	5.7	493
S9	20.8	2.7	580	1152	1478	7.8	410	89	25	119	24	399	63	0.61	4	0.94	6.4	1.2	5.4	490
S10	20.7	4.9	129	698	857	7.7	257	59	54	129	27	100	24	0.2	5	0.76	5.5	1.6	5.2	307
S11	20.8	5.6	365	1023	1128	8.4	325	88	25	130	28	312	25	0.19	6	0.85	5.7	1.4	5.9	321

End of Table 2

S S	Temp	Tur	TH	TDS	EC	pH	TA	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	F^{-}	NO_3^{-}	PO_4^{3-}	DO	BOD	COD	HCO_3^{-}
S12	20.6	4.4	356	873	1369	6.5	258	86	57	128	26	99	23	0.21	4	0.97	5.6	1.6	5.8	311
S13	18.3	1.9	324	1035	1472	7.6	368	73	51	135	14	420	64	0.1	5	1.12	6.1	1.2	6.3	355
S14	18.2	4.7	192	659	954	7.7	298	72	29	136	15	219	65	0.1	4	1.23	6.4	1.5	9.3	361
S15	18.4	6.3	432	587	853	7.5	298	87	53	134	13	221	63	0.1	6	1.56	6.4	3.4	9.5	113
S16	21.1	2.4	288	659	974	7.9	235	55	19	317	19	120	38	0.2	4	1.45	5.9	3.2	10.2	115
S17	21.2	1.2	169	398	795	8	195	54	18	118	20	121	37	0.21	5	1.54	6.2	2.9	10.9	118
S18	21.3	2.1	240	365	869	8.3	169	56	20	116	18	119	39	0.19	3	1.36	5.9	3.4	10.2	123
S19	22.4	1.8	72	250	325	8.2	186	54	19	136	23	136	24	0.5	4	1.48	6.8	3.9	10.7	112
S20	22.5	2.5	218	783	1058	7.2	218	55	18	137	22	135	25	0.49	3	1.59	6.9	3.5	10.6	123
S21	22.6	4.9	325	1182	1289	7.6	365	88	53	135	24	337	26	0.51	5	0.78	7	1.5	5.4	326
S22	21.1	3.2	321	963	1128	8.1	330	89	54	348	29	180	43	0.4	4	0.56	5.1	1.9	5.9	321
S23	21.2	2.5	115	548	845	7.9	231	57	21	149	30	181	42	0.41	5	0.94	5	1.4	5.6	402
S24	21.3	1.6	115	562	687	7.8	335	59	19	347	28	179	44	0.39	3	0.69	4.9	1.6	5.8	407
S25	24.6	5.8	343	1175	1254	7.7	324	96	57	105	31	325	20	0.5	5	0.49	5.1	1.8	5.6	304
S26	24.5	3.6	256	695	823	7.6	251	41	23	106	32	115	21	0.51	5	0.82	5	1.1	6.3	305
S27	24.4	2.9	315	1236	1598	7.9	354	87	54	104	30	362	19	0.49	5	0.67	5.2	1.7	6.2	308
S28	16.9	1.8	269	654	765	8.1	282	74	23	213	24	217	38	0.3	5	0.99	8	1.9	5.7	343
S29	16.8	1.5	214	749	954	7.5	279	75	24	212	25	218	39	0.29	6	0.88	8.1	1.6	5.4	339
S30	16.7	2.4	128	523	658	7.6	279	73	22	214	23	216	37	0.31	4	1.45	8.2	3.1	9.3	125
S31	19.1	2.6	221	786	948	7.6	199	65	25	220	33	236	29	0.4	3	1.59	7.7	3.6	10.9	112
S32	19.2	2.4	269	956	1369	6.8	201	67	24	221	34	237	28	0.5	4	1.86	7.5	3.4	10.8	115
S33	19.3	5.6	476	1536	1785	7.1	415	109	55	219	32	135	30	0.3	2	1.48	7.6	3.6	10.7	105
S34	23.1	2.6	235	762	978	6.8	291	68	22	185	23	165	98	0.6	4	1.78	8.1	3.1	11.3	106
S35	23	2.7	295	769	932	7.2	291	56	21	186	22	154	98	0.5	5	1.98	8	3.2	12..4	109
S36	23.2	1.5	124	459	615	8	145	48	23	184	24	122	99	0.6	6	0.95	7.9	1.1	5.7	358
S37	21.3	1.2	168	465	925	6.7	156	64	25	193	20	165	97	0.5	2	0.75	6.5	1.2	5.9	356
S38	22.4	1.5	302	770	945	7.2	187	92	54	392	19	126	68	0.4	5	0.56	6.7	1.3	6.2	235
S39	21.6	6.5	365	1458	1985	7.5	432	90	53	394	21	385	68	0.9	4	0.96	6.3	2.4	7.8	132
S40	22.5	2.3	278	653	873	7.9	145	75	28	197	18	235	56	1	3	0.48	6	1.8	6.5	265
Mean	21.04	3.04	258.1	779.7	1019	7.61	277.48	70.75	32.55	195.48	22.8	218.58	48.2	0.41	4.25	1.07	6.31	2.06	7.05	273.05
SD	2.02	1.55	110.45	296.16	345.77	0.44	80.55	15.76	15.23	89.47	5.81	101.67	23.24	0.23	1.1	0.39	1.04	0.91	2.45	121.33
CV	4.06	2.39	121.99	87.71	119.55	0.198	64.88	248.45	231.9	80.04	33.81	103.37	53.99	0.051	1.218	0.16	1.077	0.82	6.002	147.21

Note: * All parameters expressed in mg/L except Temp^{0} C, Turb (NTU), EC (Micro S/ Cm) and pH; SD – Standard Deviation, CV – Coefficient of Variance in %.

Table 3. Formula used to Calculate Water Quality Indices with references

S. No	Water Quality Index	Symbol	Formula	Proposed by
1	Sodium Absorption Ratio	SAR	$SAR = \frac{Na^{+}}{\sqrt{\left(\frac{\left(Ca^{2+} + Mg^{2+}\right)}{2}\right)}}$	Richards (1954)
2	Kelly's Ratio	KR	$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}}$	Kelley (1963)
3	Permeability Index	PI	$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}} \times 100$	Doneen (1964)
4	Soluble Sodium Percentage	SSP	$SSP = \frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \times 100$	Todd (1980)
5	Residual Sodium Carbonate	RSC	$RSC = \left(CO_3^{2-} + HCO_3^{-}\right) - \left(Ca^{2+} + Mg^{2+}\right)$	Gupta and Gupta (1987)
6	Residual Sodium Bicarbonate	RSBC	$RSBC = HCO_3^{-} - Ca^{2+}$	Gupta and Gupta (1987)

study, the estimation of several parameters, including Sodium Adsorption Ratio (SAR), Kelly Ratio (KR), Permeability Index (PI), Soluble Sodium Percentage (SSP), Residual Sodium Carbonate (RSC) and Residual Sodium Bicarbonate (RSBC) served as the basis for the assessment of groundwater quality for irrigation uses (Table 3).

3.2.1. Sodium adsorption ratio (SAR)

Richards (1954) defined SAR, as a measure of the amount of sodium present in groundwater that is linked to major cations like Na^+, Ca^{2+}, and Mg^{2+} and it is measured in meq/L, Based on SAR, Subba Rao (2017), classified the ground water samples in to four categories such as excellent (<10), good (10–18), doubtful (18–26) and unsuitable (>26) for irrigation.Increased hardness and decreased permeability in the soil are two effects of high salt in irrigation water (Islam et al., 2017). The spatial distribution map (Figure 3a) exposed that all groundwater samples in the study area fell under the excellent class (SAR < 10 meq/L) and were suitable for irrigation. This analysis also disclosed that there is no risk of exchangeable sodium content. This is confirmed by the analytical results, which varied from 1.22 to 6.54 meq/L. The current study is in good agreement with the results of Haritash et al. (2016) who stated that the water samples they had taken had SAR values less than 10 meq/L. The results recommended that a low SAR value is suitable for irrigation, which had no effect on crop yield.

3.2.2. Kelly ratio (KR)

Kelly's ratio is calculated with the use of cations such as Ca^{2+}, Mg^{2+}, and Na^+, except K^+. The precarious influence of sodium ion concentration in collected samples for irrigation was evaluated by Kelley (1963) using this ratio. The present findings of KR, which varied from 0.41 to 1.89 meq/L, indicated that groundwater samples fluctuated between suitable and appropriate for irrigation. The samples positioned in the centre and north-east regions of the spatial distribution map (Figure 3b) of the area under study revealed the suitability of irrigation. According to the KR classification, it has been found that some samples falling under the north-west and southern regions were appropriate for crop yield. Alharbi (2018) reported in his study that high values of the Kelly ratio might be due to the preponderant levels of Ca^{2+} and Mg^{2+} in the studied water samples.

3.2.3. Permeability index (PI)

Doneen (1964) established the permeability index (PI) to evaluate water suitability for irrigation. Use of irrigation water over an extended period of time affects soil permeability, which mostly contains the ions Na^+, Mg^{2+}, Ca^{2+}, and HCO_3^-. During the examination period, PI values varied from 43.16 to 79.87 meq/L. According to the PI's spatial variation map (Figure 3c), the southern and central regions of the research area are classified as Class I and are ideal for irrigation, while the remaining samples are classified as Class II, which means they are only moderately acceptable. Analysis revealed that none of the samples in Nilakkottai taluk were unsuitable for irrigation during the investigation period. Thus, the groundwater samples were classified as acceptable for irrigation under categories I and II based on the PI values of the study region.

3.2.4. Soluble sodium percentage (SSP)

One of the most important factors in determining the classification of irrigation water is the soluble sodium percentage (Wilcox, 1955). The results of SSP varied from 32.19 to 69.83 meq/L across all the samples. The spatial variation map (Figure 3d) of soluble sodium percentage reported that about 53% of the studied region is in the permissible class and is situated in the geographic centre of the study area. In the southern and northeastern regions of the examined area, 25% of the samples fell into the optimal category for irrigation. Higher salinity causes the establishment of salty soils that are inhospitable to plant growth, and more irrigation using water samples from these sites typically makes the water saline (Krishna Kumar et al., 2014). A higher percentage of sodium in groundwater decreases the permeability of the soil. Only 22% of the samples identified good-quality of irrigation water based on Todd (1980) classification. The results of both SSP and SAR found some variation, and this could be substantiated by the high concentration of K^+ in the study area. Alfarrah and Walraevens (2018) proclaimed that salty water intrusion and agricultural runoff were the causes of the elevated potassium ion content in ground water.

3.2.5. Residual sodium carbonate (RSC)

RSC is one of the most popular method for irrigation water determination. This may be computed by CO_3^{2-} and HCO_3^- concentration levels in relation to Ca^{2+} and Mg^{2+} ions. According to Subba Rao (2017), water quality is good for irrigation with an RSC value less than 1.25 meq/L and moderate if it is from 1.25 to 2.50 meq/L, while RSC greater than 2.50 meq/L is not acceptable. The concentration of Na^+ in the soil can rise, and the quality of the irrigation water can be lowered by Ca^{2+} and Mg^{2+} precipitation. Analytical results reported that the samples such as S3, S5, S9, and S33 showed a negative value of RSC and were suitable for irrigation, indicating safe water quality. The present findings are in accordance with the results of Haritash et al. (2016), whose research revealed an RSC value that was negative. The spatial distribution map (Figure 3e) revealed that the centre and south-west regions had high RSC values, which indicates an unsuitable category for irrigation purposes and is harmful for plant growth. The large magnitude of RSC that causes the dissociation of organic matter can damage the physical qualities of the soil. This causes the soil to become stained black when it dries (Srinivasamoorthy et al., 2014). It can be neutralized by adding gypsum or sulfuric acid. The rest of the water samples had an RSC value ranging from 1.25 to 2.5 meq/L, indicating that the water is acceptable for irrigation according to Subba Rao (2017).

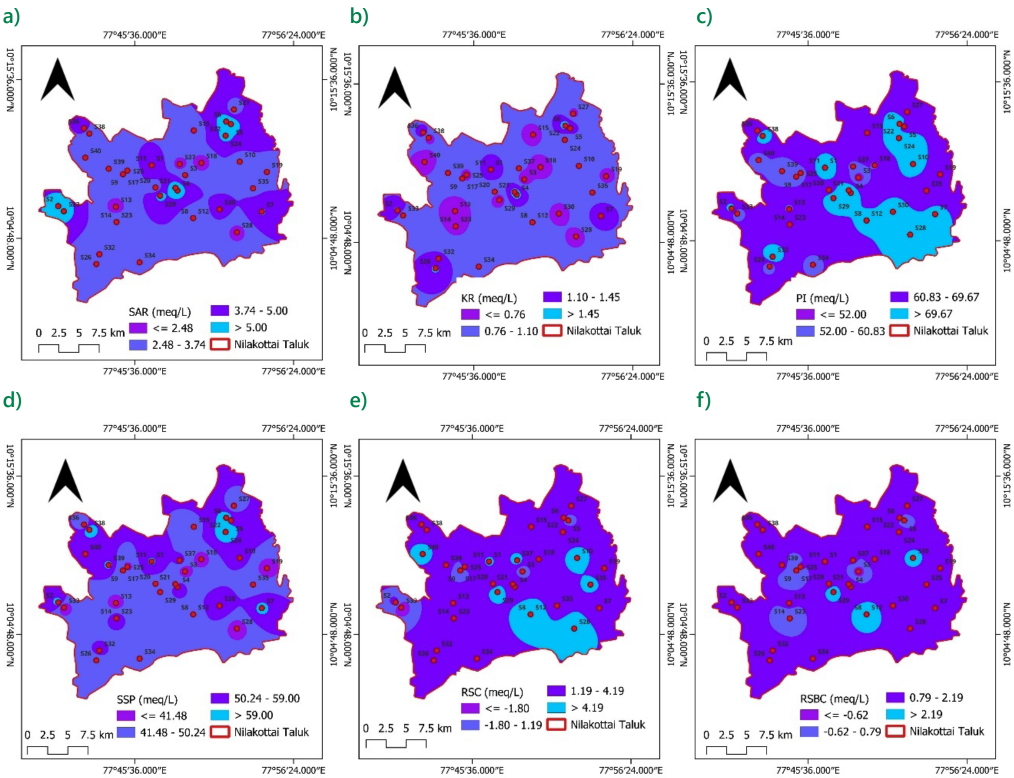

Figure 3. Irrigation water quality indices: a) SAR; b) KR; c) PI; d) SSP; e) RSC; f) RSBC

3.2.6. Residual sodium bicarbonate (RSBC)

The RSBC an extensive index used to judge the suitability of irrigation. It is used to assess the alkalinity hazards associated with high HCO_3^- and Ca^{2+} ions. The RSBC significantly influences the pH, Electrical Conductivity (EC) and SAR of the irrigation water. In the examination period, RSBC values varied from –2.57 to 3.82 meq/L. Soil texture may deteriorate with the constant use of water containing Na_2CO_3 and $NaHCO_3$ for irrigation. Nevertheless, it is better suited for irrigation when there is an abundance of CO_3^{2-} and HCO_3^- of Ca^{2+} and Mg^{2+} in the water. The spatial distribution map (Figure 3f) explored that all samples in the study area were within less than 5 mg/L and satisfactory for irrigation. Summary statistics of calculated WQIs of the study area were tabulated in Table 4.

3.3. Multivariate statistical analysis of hydrogeochemical data

Multivariate statistical techniques can be used to simplify and arrange large datasets in order to yield insightful results (Gaagai et al., 2017; Gad et al., 2020b). In this study, two multivariate statistical methods Viz. principal component analysis (PCA), and cluster analysis (CA) were applied to evaluate the physicochemical variables of our groundwater samples.

3.3.1. Principal component analysis (PCA)

In hydrological investigations, PCA is frequently used to load the hierarchy of PCs, minimize the number of variables, extract relevant information, and depict the interac-

Table 4. Summary statistics of calculated WQIs of the study area

Methods	Range of WQI	Water class	Sampling sites	
			No. of samples	% of sampling sites
SAR (Subba Rao, 2017)	<10	Excellent	All samples	100%
	10–18	Good	Nil	–
	18–26	Doubtful	Nil	–
	>26	Unsuitable	Nil	–
KR (Kelley, 1963)	<1	Suitable	26	65%
	1–2	Marginal	14	35%
	>2	Unsuitable	Nil	–
PI (Doneen, 1964)	>75%	Excellent	13	32.5%
	25–75%	Good	27	67.5%
	<25%	Unsuitable	Nil	–
SSP (Todd, 1980)	<20	Excellent	Nil	–
	20–40	Good	9	22%
	40–60	Permissible	21	53%
	60–80	Doubtful	10	25%
	>80	Unsuitable	Nil	–
RSC (Subba Rao, 2017)	<1.25	Good	4	10%
	1.25–2.5	Moderate	9	22%
	>2.5	Not acceptable	27	68%
RSBC (Gupta, 1987)	<5	Satisfactory	All samples	100%
	5–10	Marginal	Nil	–
	>10	Un Satisfactory	Nil	–

tion of minerals in the aquifer. In order to prevent multicollinearity between model parameters, principal component analysis (PCA) extracts eigenvalues from the original dataset and creates new PCs that are orthogonal to one another after varimax rotation (Abou Zakhem et al., 2017; Ravikumar & Somashekar, 2017; Pan et al., 2019). According to Abou Zakhem et al. (2017), Selvakumar et al. (2017) and Pan et al. (2019), PCs with eigenvalues larger than unity are deemed significant, and each significant PC accounts for a percentage of the dataset's overall variance. Liu et al. (2003) categorized factor loads into three categories: "poor" for 0.30–0.50, "medium" for 0.50–0.75, and "strong" for >0.75.

Varimax with Kaiser normalization was used to summarize the dominating factors based on the scree plot (Figure 4) with an eigenvalue greater than 1.0. Four principal components (PC1, PC2, PC3 and PC4) were retained, as shown in Table 5. Two disparate sources, especially geogenic and anthropogenic, have been identified from the four principal components. These two sources are major controlling factors for groundwater samples in the study area.

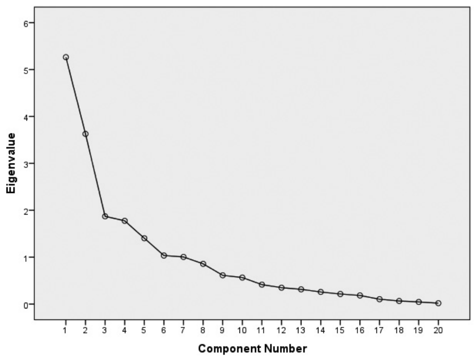

Figure 4. Scree plot

PC1 explained that 62.07% of the total variance has substantial loading on TH, Ca^{2+}, TDS, EC, TA, Mg^{2+}, Cl^- and bicarbonate. This could be related to both geogenic and anthropogenic sources. Geogenic source merely from rock weathering and the ion exchange process. Anthropogenic sources may include domestic waste and uncontrolled fertilization. This study was supported by the results of Ravikumar and Somashekar (2017), where they described that the loadings of EC, TDS, TH, Ca, and Mg on PC1 collected the groundwater samples from the Varahi River basin. PC2 shows the dominance of phosphate, DO, BOD, and COD with a total variance of 69.45%. This factor is purely controlled by anthropogenic inputs such as fertilizers, the percolation of sewage, and industrial effluents, which constitute non-point sources of contamination.

PC3 reflects a favourable loading on sodium (0.533) and sulphate (0.801) with a total variance of 74.84%. This could be related to both geogenic and anthropogenic inputs. Na^+ content could be caused by plagioclase feldspar distribution, and sulphate may originate from the oxidation of sulphur compounds. PC4 indicates loading only on nitrate (0.556) with a total variance of 80.12%. The application of agrochemicals contributes to this PC.

Table 5. Principal component analysis of ground water samples of the study area

Parameters	Components			
	PC1	PC2	PC3	PC4
Temp	.015	–.410	–.164	.196
Turb	.635	.176	–.372	–.162
TH	.794*	.226	.133	–.071
TDS	.893*	.157	.035	.236
EC	.847*	.246	.101	.164
pH	–.153	–.349	–.379	–.222
TA	.767*	.026	–.031	–.127
Ca^{2+}	.820*	.176	.123	–.091
Mg^{2+}	.759*	–.016	–.130	–.028
Na^+	.071	–.045	.533**	.107
K^+	.241	.222	–.476	.333
Cl^-	.616**	–.142	.267	–.246
$SO4^{2-}$	–.123	–.112	.801*	–.154
F^-	.155	–.148	.220	.731
NO_3^-	.164	–.193	–.266	.556**
PO_4^{3-}	–.356	.820*	.061	–.049
DO	–.153	.651**	.319	–.082
BOD	–.230	.862*	–.125	.109
COD	–.239	.722**	–.179	.102
HCO_3^-	.623**	.005	.048	.025
Eigen values	1.754	1.402	1.025	1.003
% of variance	62.068	7.378	5.396	5.279
Cumulative %	62.07	69.45	74.84	80.12

Note: *Strong (p > 0.75), **Moderate (0.5– 0.75); Rotation method: Varimax with Kaiser normalization.

3.3.2. Cluster analysis (CA)

According to a study conducted by Belkhiri et al. (2010), Ward's method produces a higher percentage of correctly identified items than other methods. As a result, the current work applies cluster analysis using the Euclidean distance and adopts Ward's clustering method (Hinge et al., 2022).

The dendrogram of 20 physicochemical parameters is categorized into three main clusters. Grouped variables under each cluster are shown in Figure 5a. Based on the results, TDS and EC form cluster 1. This close association is attributed to dissolved constituents that can enhance ionic contents. High concentration of TDS and EC mainly originated from anthrophorgenic activities which includes the discharge of domestic and agricultural waste. The second cluster revealed an association between the evaporation parameters, such as TDS, sodium, chloride, calcium, sulphate, TH, and TA. These results coincided with the results of Subba Rao et al. (2024) studied the evaporation dominance of Titrol block of Jagatsinghpur district, Odisha due to increase in concentrations of Na^+ ,Cl^- and TDS. Since evaporation predominates in the majority of the samples in the research area, the concentration of the aforementioned parameters tends to increase as evaporation rates rise under specific climatic conditions.

Finally, the third cluster showed a close association between temperature, potassium, calcium, magnesium, sulphate, total hardness, total alkalinity, chloride, and bicarbonate, revealing that the study area was dominated by both temporary and permanent hardness. Major dominance of calcium and magnesium due to the chemical constituents of ground water and reverse cationic exchange. The clusters, which are further grouped into 2 subgroups, contain 13 parameters in one subgroup and 5 parameters in another subgroup, indicating the probable same origin of these parameters.

In addition to parameter grouping, sampling site classification was also performed, and a dendrogram was generated (Figure 5b). Mainly, five clusters were formed, which were further classified into subgroups. Cluster I comprise sampling sites 2 to 18, sampling sites 12 to 23 form cluster 2, cluster 3 includes 18 to 28, and cluster 4 groups 23 to 33 and 33 to 35 form cluster 5. The remaining sampling sites were clustered into subgroups. The basic principles involved in the similarity and dissimilarity of sampling sites are mainly affected by land use and industrial structure.

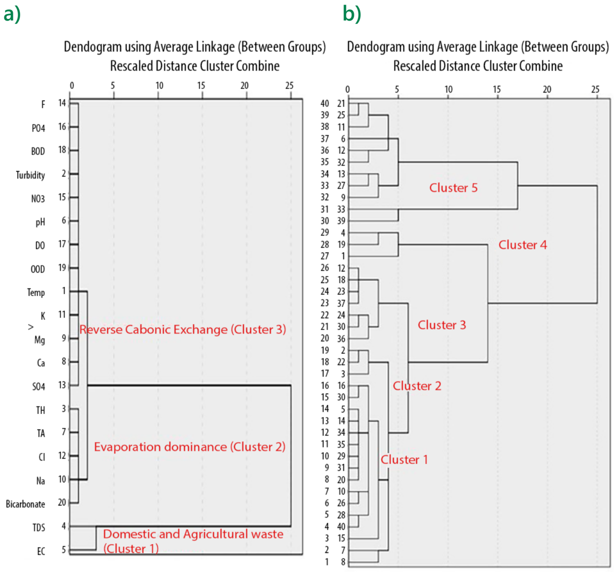

Figure 5. Dendrogram: a) Parameters; b) Sampling sites

3.4. Hydrofacies diagram

3.4.1. Durov diagram

Durov's plot is another important hydrofacies diagram that is useful for identifying the hydrochemical processes in water, categorizing various water mixing types, determining the ions present, and determining reverse ion exchange processes (Durov, 1948; Li et al., 2016). The Durov plot (Figure 6) showed that the samples in fields 1 and 2 with dominant HCO_3^--Ca^{2+} and Mg^{2+} indicate the water originating from calcite and dolomite in the research region. According to samples from fields 4 and 5, calcium-containing minerals like gypsum and calcite readily dissolve in water. The following process governs the dissolution of calcite in the soil zone.

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^-. \quad (1)$$

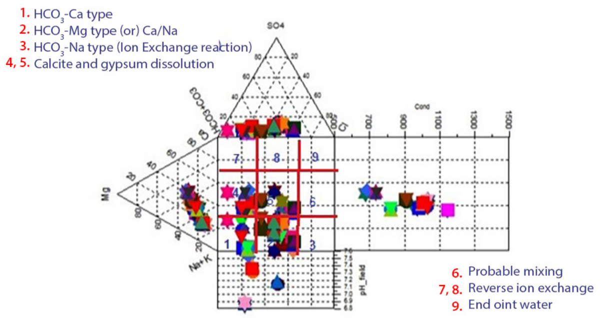

Figure 6. Durov diagram

4. Conclusions

In this work, the effectiveness of a group of various water quality indices for forecasting the water quality of Nilakkottai Taluk, Dindigul District, Tamil Nadu was investigated based on 40 groundwater samples. Irrigation water quality indices revealed that groundwater samples were between suitable and permissible class. The heterogeneity in ground water quality in the entire basin is due to changing cropping pattern, monotonous crops and rainfall influence. According to PCA, the occurrence of four essential components demonstrated the influence of significant ions on ground water quality in the studied region. These findings may be explained by evaporation, weathering, rock water interaction and anthropogenic sources. These results were further supported by cluster analysis. To illustrate the hydrochemical facies in groundwater, durov plots would be suitable, and classified the Ca-HCO_3 type of water. This is confirmed that weathering of parent rocks and carbonate dissolution are significant sources of groundwater in this region. This study inferred that an efficient and useful method for evaluating groundwater quality and development in any part of the world is to employ physicochemical factors, multivariate modelling, water quality indices backed by GIS techniques and hydofacies diagrams. The outcomes of this study would be helpful for decision-makers, farmers and local people. This study demonstrated that index-based irrigation water quality can be used to identify the number of wells that are appropriate for irrigation systems and also preventing crop damage. In order to replenish ground water, state government and non-government organization (NGO) should support to turn excavated wells and abandoned bore wells into artificial recharge structures and rainwater harvesting structures in the study area.

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