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Groundwater quality analysis and mapping using GIS techniques: a case study from northwest Türkiye

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Abstract

The İnegöl Plain, located in northwestern Türkiye, suffers from environmental problems such as air, water, and soil pollution due to intensive and uncontrolled human activities. Recently, the availability and quality of groundwater in plains have been adversely affected to an alarming degree. Therefore, it is necessary to determine and map the groundwater quality in the İnegöl Plain. This study aimed to determine and map the groundwater quality in the İnegöl Plain. Within the scope of the study objective, a dataset consisting of analysis results from water samples taken from 107 wells located within the plain boundaries was used. The dataset contained ten different parameters. These data were analyzed using comprehensive statistical methods. These assessments were supported by Geographic Information System (GIS)-based mapping and analytical tools. The results of the study showed that according to the drinking and utility water quality index results of the samples taken from the wells in the plain, the Drinking Water Quality Index (DWQI) (74.8%) and Irrigation Water Quality Index (IWQI) (87.8%) were acceptable. According to these results, it was determined that the DWQI and IWQI classes are weak, very weak, and unsuitable in parts of the plain near the Bursa-İnegöl highway.

Introduction

Water is a unique natural resource because its total global quantity remains constant compared with other renewable resources (Pius et al., 2012). Groundwater is particularly important for many people worldwide because it is used for both drinking and domestic purposes (Nas and Berktay, 2010). In recent years, decreases in surface water due to severe droughts have increased demand for groundwater. Therefore, increased water use alters the level and quality of the groundwater (Taş and Davarcı, 2017). Globally, anthropogenic activities such as urbanization, industrial development, and increased agricultural production have also contributed to the deterioration of groundwater quality (Kawo and Karuppannan, 2018). Groundwater pollution is one of the most serious problems worldwide (Sadat-Noori et al., 2014). Therefore, the assessment of groundwater quality is critical for the protection and sustainable management of groundwater resources, which are variably sensitive to constantly increasing human-induced physical and chemical pressures and climate change (Machiwal et al., 2018).

Groundwater quality is defined as a measure of the suitability of water for a specific use, based on selected physical, chemical, and biological characteristics (Cordy, 2001). Before groundwater can be used for any purpose, quality parameters must be determined according to the intended use (Özşahin, 2013). However, owing to the spatial variability of multiple pollutants and the wide variety of measurable indicators (chemical, physical, and biological), it is difficult to define the overall water quality status (Kavurmaci, 2016). Geographic Information System (GIS)-based methods have proven to be powerful tools for the regular assessment and monitoring of groundwater quality in recent years. A GIS-based groundwater quality index that numerically indexes and synthesizes existing water quality data according to international standards has been proposed (Babiker et al., 2007).

İnegöl is one of Türkiye's leading districts in agriculture, industry, and tourism (BEBKA, 2023). It has been recorded that various types of environmental problems, such as air (İskan and Koç, 2021), water (İşlek, 2012), and soil (Menteşe, 2015) problems, have emerged in the district center, which is located on a fertile alluvial plain corresponding to the İnegöl plain, due to intensive and uncontrolled human activities, such as unregulated industrial waste disposal and intensive chemical use in agriculture. The reason for these emerging problems is that such activities disrupt the natural filtration processes of the alluvial plain and introduce hazardous substances into the environment. In particular, there has been a tremendous increase in the demand for groundwater owing to the acceleration of urbanization and industrialization (Yüceşahin, 2003). However, the availability and quality of groundwater in plains are adversely affected at an alarming rate by anthropogenic activities, such as the overuse and pollution of groundwater basins (industrial, domestic, and agricultural) (Ünver, 2010; İşlek, 2012; Davraz and Ünver, 2014; Taş and Davarcı, 2017; Dorak et al., 2019). Therefore, it is necessary to determine and map the spatial distribution of groundwater quality on the İnegöl Plain. According to the World Health Organization (WHO), approximately 80% of all human diseases are waterborne (WHO, 2017). When groundwater is polluted, it becomes difficult to prevent pollutants from reaching their source, restore the water to its original state, and bring it to the appropriate quality. Therefore, it is imperative to monitor groundwater quality regularly and devise methods to protect it from pollution (Panneerselvam et al., 2020; Ram et al., 2021).

Despite various local reports, there is a significant lack of high-resolution integrated spatial modeling that determines and maps the spatial distribution of groundwater quality in the İnegöl Plain. The novelty of this study lies in its diagnostic approach, which utilizes a dense sampling network (n=107) and incorporates the Coefficient of Variation (CV) as a statistical marker to differentiate between natural rock-water interactions and localized anthropogenic "hotspots." Unlike previous studies, this research provides comprehensive geospatial mapping of both the Drinking Water Quality Index (DWQI) and Irrigation Water Quality Index (IWQI), offering an original decision-support framework for identifying specific zones of industrial and agricultural impact in northwest Türkiye.

This study aims to determine the quality and evaluate the spatial distribution of groundwater in the İnegöl Plain. This study employed a multi-method approach combining hydrogeochemical analysis, spatial statistics, and GIS-based water quality indexing. Various groundwater quality indices have been formulated to determine the appropriateness of water supplies for multifaceted uses (Barakat et al., 2018; 2020; Ponsadailakshmi et al., 2018; Sunkari et al., 2020). Physical and chemical parameters (pH, electrical conductivity, and major ions) were analyzed from groundwater samples collected from 107 wells, comprising 96 DSI-monitored wells and 11 privately owned wells. Statistical analysis included descriptive statistics, normality testing (Shapiro-Wilk), correlation analysis (Pearson), and outlier detection to characterize hydrogeochemical variability. Furthermore, the DWQI and IWQI were calculated separately to assess the suitability of drinking and irrigation. This integrated framework enables the quantitative assessment of natural versus anthropogenic controls on groundwater quality and provides actionable recommendations for sustainable aquifer management.

Materials and Methods

Study Area

The study area was the İnegöl Plain within the borders of Bursa Province, which ranks fourth in Türkiye in terms of population (Figure 1). Geographically, this area is located between 29°23′54.272′′ - 29°41′46.305′′ east longitude and 40°01′00.023′′ - 40°07′29.547′′ north latitude. The study area, shaped by rivers originating from the Uludağ, Domaniç, and Ahi mountains, covers an area of 145 km². The study area, which corresponds to the base of the İnegöl Basin and exhibits characteristic geological, geomorphological, and hydrographic features, consists of Quaternary alluvium deposited by rivers (Ardel, 1947; Hoşgören, 1975). The average annual temperature is 13.8 °C, and the average annual total precipitation is 427 mm (Menteşe, 2015; Mentese and Tagil, 2016).

The land use pattern in the study area is predominantly agricultural and settlement areas (Başkent and Kadioğullari, 2007). Owing to its fertile alluvial soils and favorable climate, the İnegöl Plain is a

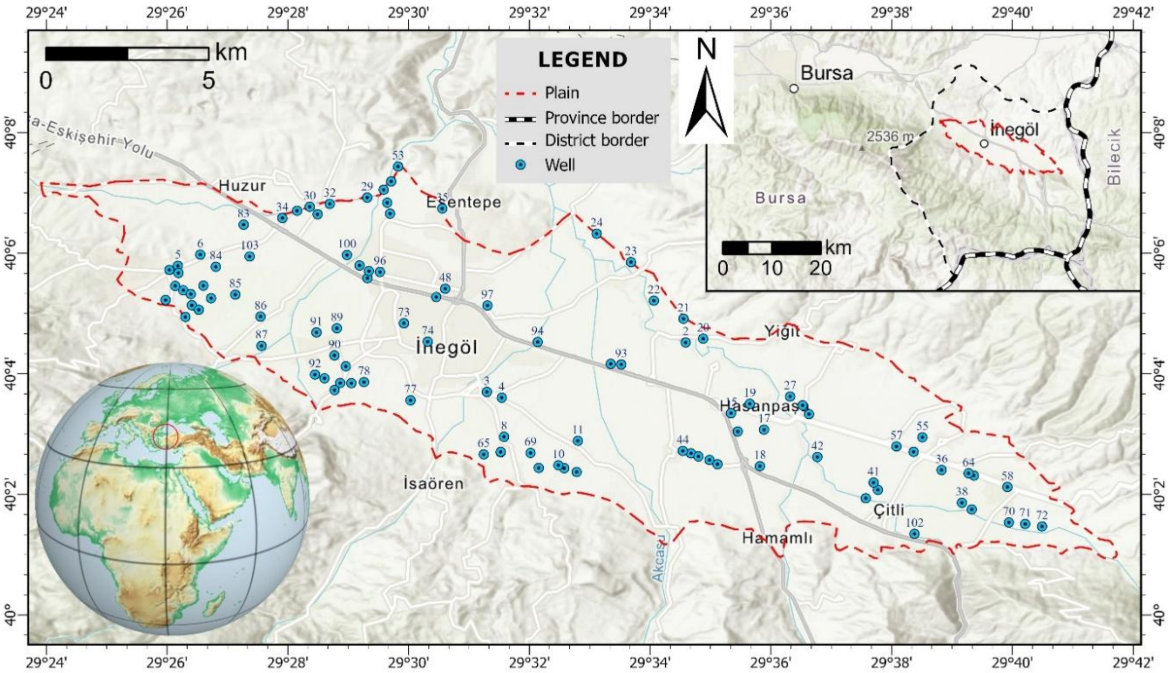

Figure 1. Location of the study area and distribution map of groundwater wells

center for high-value intensive agriculture (Yüceşahin, 2003). The primary agricultural products cultivated in the valley include pome and stone fruits (specifically peaches, pears, and apples), a wide variety of vegetables (tomatoes and peppers), and field crops such as sunflowers and cereals (Bilgili and Zere Taşkın, 2025). To maintain high yields, intensive farming practices are strictly implemented, characterized by extensive irrigation and heavy fertilization regimes (Tas and Davarcı, 2017). Irrigation is primarily supported by groundwater from shallow alluvial aquifers and surface water resources (rivers and dams etc.). Furthermore, the application of nitrogen-phosphorus-potassium (NPK) fertilizers and sulfate-based soil conditioners is widespread across plain orchards and vegetable plots. The study area is a plain in Bursa province with the highest annual average consumption of triple superphosphate (TSP) fertilizer (Katip, 2020). The extensive use of these chemical inputs, coupled with return flows from the furrow and drip irrigation systems, constitutes a significant potential source of nitrate, potassium, and sulfate leaching into the underlying groundwater system.

However, land-use patterns have changed significantly over time owing to several factors, including unregulated management actions, social pressures, and demographic movements (Başkent and Kadioğullari, 2007). In recent years, economic activities have diversified and increased in parallel with rapid population growth and urbanization (Erdoğan, 2019). Anthropogenic changes associated with increased industrial activities, particularly in the furniture and textile sectors, have led to various environmental problems. These environmental issues, which pose a threat to the region's sustainable development, include air-water-soil pollution, solid and hazardous waste management, and degradation of natural ecosystems (Akgün, 2022).

Materials

The hydrogeochemical dataset utilized in this study consists of water analysis results from 107 wells located across the study area. These data were compiled from İşlek's (2012) master's thesis, which represents a comprehensive hydrogeological survey of the study area. The dataset comprises 96 wells monitored by the General Directorate of State Hydraulic Works (DSİ) and 11 privately owned wells. To facilitate systematic evaluation, the raw data were organized and transferred into Microsoft Excel for pre-processing, data cleaning, and statistical calculations (Figure 2).

Methods

Analysis Parameters: According to the study dataset, ten different parameters were analyzed in water samples taken from wells in the study area: pH, electrical conductivity (EC), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), chloride (Cl^-), bicarbonate (HCO_3^-), and total hardness (TH).

Hydrogeochemical Indices and Calculations: In addition to the measured parameters, the Sodium Adsorption Ratio (SAR) and Sodium Percentage (%Na) were calculated to assess irrigation suitability. The SAR

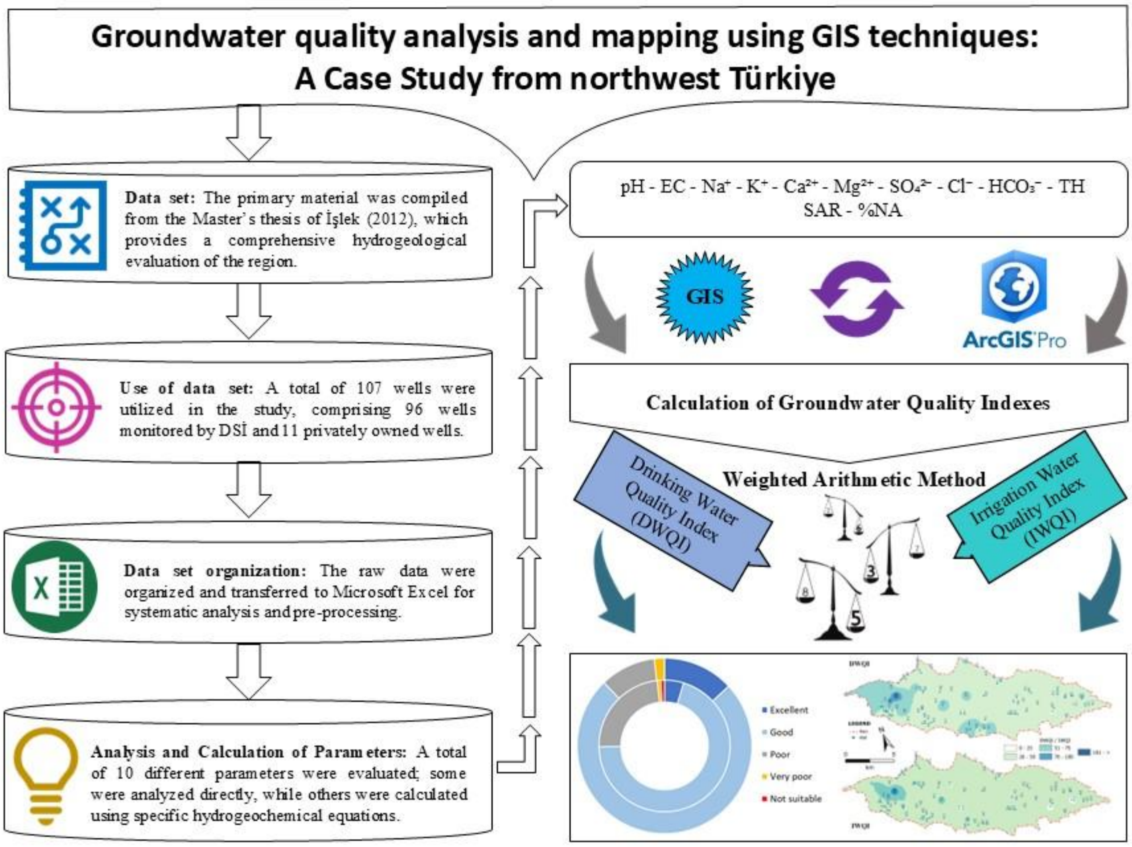

Figure 2. Methodology flowchart

value was determined using the following formula (Richards, 1954).

$$SAR = Na/[\frac{Ca + Mg}{2}]^{1/2}$$

where SAR = Sodium Adsorption Ratio, Na = Sodium, Ca = Calcium, and Mg = Magnesium.

The percentage of sodium (%Na) was determined using the formula proposed by Wilcox (1948) as follows:

$$\%Na = \frac{Na}{(Na + K + Ca + Mg)} \times 100$$

where %Na = Sodium Percentage, Na = Sodium, K = Potassium, Ca = Calcium, and Mg = Magnesium. The meq/l values of these parameters were used for the calculations.

Analytical data from the study area and the parameters derived from these data were used to calculate the DWQI and IWQI. These indices were regulated according to the standards used by the Turkish Standards Institute (TSE 266), the European Union (EU), and the WHO (Table 1).

Table 1. Drinking water standards for water quality parameters (MUNPAPRACR, 2022)

Parameters	Drinking water standards		
	TSE 266	EU	WHO
pH	6.5-9.5	6.5-9.5	6.5-9.5
EC (µS/cm)	2500	2500	2500
Na^+ (mg/L)	175	200	200
K^+ (mg/L)	12	-	-
Ca^{2+} (mg/L)	200	-	100
Mg^{2+}(mg/L)	50	50	-
SO_4^{2-}(mg/L)	250	250	250
Cl^- (mg/L)	250	250	250
HCO_3^-(mg/L)	600	-	-
TH (mg/L)	200	-	500

Accordingly, only 10 parameters were used for the DWQI, while both the 10 parameters and the SAR and %Na calculation results were used for the IWQI. The results were combined using a weighted arithmetic method. The relevant indices were calculated using the following formulas (Ram et al., 2021).

$$DWQI \ \& \ IWQI = \frac{\sum_{i=1}^{n} W_i \times Q_i}{\sum_{i=1}^{n} W_i}$$

where DWQI = Drinking Water Quality Index, IWQI = Irrigation Water Quality Index; n is the number of variables or parameters; Wi is the unit weight of parameter i; and Qi is the quality index or subscript of parameter i.

The unit weight (Wi) of various parameters was determined using the following equation, which is inversely proportional to the recommended standards for the relevant parameters (Ram et al., 2021).

$$W_i = K/S_n$$

where Wi is the unit weight of parameter i, Sn is the standard value of parameter i, and K is a proportionality constant. The value of K is assumed to be "1" and is calculated using the following equation:

$$K = 1/\sum(\frac{1}{S_n})$$

The quality index or sub-index (Qi) value was calculated using the following equation provided below (Ram et al., 2021).

$$Q_i = 100[\frac{V_o - V_i}{S_n - V_i}]$$

where Vo is the observed value of parameter i at a specific sampling point, Vi is the ideal value of parameter i in pure water, and Sn is the standard permissible value of parameter i.

The calculated values for SAR, %Na, and the water quality indices (DWQI and IWQI) were categorized according to the widely accepted international classification standards. Specifically, the irrigation suitability classes were based on Richards (1954) for SAR and Wilcox (1948) for %Na, whereas the quality index ratings followed the thresholds established by Ram et al. (2021), Islam et al. (2025), and WHO standards (Table 2).

Statistical and Geospatial Analysis: To facilitate systematic evaluation, raw hydrogeochemical data were organized and processed using Microsoft Excel software. Descriptive statistical analyses, including mean and Coefficient of Variation (CV), were performed to identify spatial heterogeneity and potential anthropogenic hotspots. The spatial distribution of all parameters and indices was modeled using Geographic Information System (GIS) techniques. Specifically, the Inverse Distance Weighted (IDW) interpolation technique was applied to generate continuous thematic maps. IDW is an effective tool for representing localized variations in groundwater quality (Magesh et al., 2013; Kawo and Karuppannan, 2018; Ahmad et al., 2021). All geospatial modeling and mapping were executed using ArcGIS Pro (Version 3.6.0) software.

Table 2. Commonly used classifications for categorizing SAR, %Na and DWQI/IWQI parameters

SAR	Class	%Na	Class	DWQI / IWQI	Class
< – 10	Very good	< – 20	Very Good	0 – 25	Excellent
10 – 18	Good	20 – 40	Good	26 – 50	Good
18 – 26	Moderate	40 – 60	Usable	51 – 75	Poor
26 – >	Poor	60 – 80	Use with Caution	76 – 100	Very poor
		80 - >	Harmful, Unusable	101 – >	Not suitable

Results

The study area corresponded to a permeable hydrogeological environment. In particular, the fact that it is surrounded by impermeable and low-permeability units around the plain has led to direct storage of groundwater in the plain bed. Therefore, the alluvial deposits covering the study area act as important aquifers (İşlek, 2012).

The study area has a significant potential for groundwater reserves. This potential was determined to be 40 m/yr (Akgün, 2022). Groundwater levels have gradually declined over time. Due to excessive extraction, there was a noticeable downward trend in the groundwater level in the study area. While water was extracted from a depth of several meters before 1975, it was extracted from a depth of 10-15 meters in 2000 and from a depth of 35-40 meters today (Yüğrük, 2014).

Groundwater in the study area is allocated for use primarily for industrial and agricultural purposes as well as for drinking and domestic use, park and garden irrigation, and firefighting. The study area also has geothermal resources that are used for thermal tourism (MoEUCC, 2024). As the study area is one of the most populous areas in Bursa Province, it is impossible to prevent unplanned settlements and industrialization, which are developing rapidly due to the rapidly increasing population. Furthermore, in the study area, which has first-class agricultural land, underground water wells can be drilled without permission or licenses, owing to both unplanned industrialization and intensive agricultural activities. Thus, increasing water withdrawals in the study area causes changes in the quality and level of groundwater as well as its level (Tas and Davarcı, 2017). It has been determined that the city of İnegöl and its surrounding areas, where urbanization and industrialization are intense, correspond to areas with high groundwater extraction (İşlek, 2012). In this area, the groundwater level declined continuously.

According to the descriptive statistics of the 107 well samples analyzed in this study, the pH values range from 6.4 to 10.0, with an average of 7.41 and a low coefficient of variation (CV) of 6.07%, indicating relatively stable and uniform conditions across the study area. In contrast, other parameters exhibited significant spatial variability. The EC ranged from 272.1 to 1313.0 µS/cm (avg: 710.3 µS/cm) with a CV of 30.07%. Notably, high variability was observed for sodium and calcium, with CV values of 57.95% and 48.45%, respectively (Table 3). Na concentrations ranged from 8.28 to 175.9 mg/L (avg: 54.7 mg/L), while calcium values ranged from 1.96 to 194.0 mg/L (avg: 58.0 mg/L). According to Wilding's classification (Wilding, 1985), CV values exceeding 35% suggest high heterogeneity, implying that the concentrations of sodium and calcium in the İnegöl Plain are likely influenced by localized anthropogenic activities, such as industrial discharge or agricultural runoff, rather than purely natural hydrogeochemical processes.

According to the Shapiro-Wilk normality test results, only the bicarbonate parameter showed a normal distribution ($p=0.388>0.05$). All other parameters showed a significant deviation from the normal distribution ($p<0.05$). The lowest p values were observed in the potassium ($p=7.40\times10^{-17}$) and chloride ($p=4.63\times10^{-16}$) parameters (Table 4).

Table 3. Descriptive statistics of water quality parameters (Calculated based on data from İşlek, 2012).

Parameter	Minimum	Average	Maximum	Standard Deviation	CV (%)	Median
pH	6.4	7.41	10.0	0.45	6.07	7.5
EC (µS/cm)	272.1	710.3	1313.0	213.6	30.07	730.0
Na^+ (mg/L)	8.28	54.7	175.9	31.7	57.95	52.0
K^+ (mg/L)	0.35	7.37	93.8	12.5	169.61	2.74
Ca^{2+} (mg/L)	1.96	58.0	194.0	28.1	48.45	54.9
Mg^{2+} (mg/L)	3.03	30.2	86.3	14.5	48.01	29.8
SO_4^{2-} (mg/L)	1.44	57.6	198.4	42.7	74.13	46.1
Cl^- (mg/L)	0.0	27.4	214.1	26.0	94.89	24.8
HCO_3^- (mg/L)	97.6	352.6	641.9	92.1	26.12	342.9
TH (mg/L)	0.0	21.9	46.3	11.8	53.88	22.0

Table 4. Shapiro-Wilk normality test results (Calculated based on data from İşlek, 2012).

Parameter	Test Statistic	p-value	Normal Distribution
pH	0.871	3.36×10^{-8}	No
EC (µS/cm)	0.958	0.002	No
Na^+ (mg/L)	0.934	4.67×10^{-5}	No
K^+ (mg/L)	0.533	7.40×10^{-17}	No
Ca^{2+} (mg/L)	0.925	1.46×10^{-5}	No
Mg^{2+}(mg/L)	0.967	0.008	No
SO_4^{2-}(mg/L)	0.890	2.33×10^{-7}	No
Cl^- (mg/L)	0.577	4.63×10^{-16}	No
HCO_3^- (mg/L)	0.987	0.388	Yes
TH (mg/L)	0.968	0.011	No

Table 5. Outlier analysis results (IQR method) (Calculated based on data from İşlek, 2012).

Parameter	Number of Outliers	Percentage (%)	Lower Limit	Upper Limit
pH	4	3.74	6.5	8.1
EC (µS/cm)	13	12.15	306.0	1126.0
Na^+ (mg/L)	2	1.87	-35.03	134.5
K^+ (mg/L)	19	17.76	-3.62	11.24
Ca^{2+} (mg/L)	2	1.87	-12.66	125.58
Mg^{2+}(mg/L)	1	0.93	-13.41	74.35
SO_4^{2-}(mg/L)	6	5.61	-42.92	144.1
Cl^- (mg/L)	8	7.48	-5.68	51.06
HCO_3^- (mg/L)	3	2.80	140.4	579.6
TH (mg/L)	0	0.00	-9.04	55.06

According to the results of the outlier analysis performed using the IQR method, the highest number of outliers was detected for the potassium parameter, accounting for 17.76% (19 samples) of the total samples. Other outliers were observed in the EC (12.15%, 13 samples) and chloride parameters (7.48%, eight samples). No outliers were detected for the total hardness values (Table 5).

When evaluating the results of the correlation analysis between the parameters, the strongest positive correlation was found between calcium and magnesium levels ($r=0.677$, $p<0.01$). Moderate positive correlations were observed between EC and calcium ($r=0.546$) and magnesium ($r=0.563$) levels. Additionally, negative correlations were detected between pH and EC ($r=-0.363$) and between sodium and magnesium ($r=-0.519$).

Groundwater Quality Parameters

The spatial distribution and concentration levels of groundwater quality parameters in the İnegöl Plain are governed by a complex interplay between natural hydrogeochemical processes and intensive anthropogenic activities. The CV values calculated for each parameter served as a critical diagnostic tool for differentiating between these influences.

pH: In the present study, pH values exhibited a wide range from 6.4 to 10.0. While the majority of the samples clustered around the neutral-to-alkaline average (7.41) due to the natural carbonate-bicarbonate buffering capacity of the alluvial aquifer, the extreme alkaline value of 10.0, indicating significant localized anomalies. Such high pH levels (> 9.0) in the İnegöl Plain are primarily attributed to intensive industrial activities, specifically the discharge of alkaline wastewater from textile and furniture processing plants. This correlation between industrial effluents and high groundwater alkalinity is well-documented in similar industrial basins worldwide, such as the Nile Delta and industrial corridors in Southeast Asia, where alkaline detergents bypass natural soil buffering (Abdel-Satar et al., 2017; Chintalapudi et al., 2017).

EC: The EC values in the study area ranged from 272.1 to 1313 µS/cm, with an average of 710.3 µS/cm. The moderate CV (30.07%) suggests the dual influence of natural and anthropogenic factors. The increase in EC towards the slopes of the Uludağ and Domaniç Mountains is primarily attributed to intensive rock-water interactions. This phenomenon mirrors findings from the Himalayan and Alpine foothills, where the initial mineralization of groundwater is driven by the dissolution of crystalline basement rocks in recharge zones (Singh et al., 2008). Conversely, localized peaks in the central plain point to anthropogenic loading, consistent with “urban fingerprints” found in Nigerian and Indian aquifers, where domestic sewage significantly elevates ionic conductivity (Edet, 1993).

Sodium: In the study area, the sodium content exhibited a substantial variation, ranging from 8.28 mg/L to 175.9 mg/L with an average of 54.7 mg/L. A high CV (57.95%) indicates significant spatial heterogeneity, which is driven by both natural and anthropogenic factors. The lower concentrations represent the natural background levels derived from the weathering of silicate minerals (such as feldspars) within the surrounding crystalline rocks of the Uludağ and Domaniç Mountains. Global studies indicate that, while silicate weathering provides a baseline, concentrations exceeding 100 mg/L in alluvial plains are typically indicative of anthropogenic salt loading or cation exchange processes (Appelo and Postma, 2005). In İnegöl, high peaks near settlements, such as Kurşunlu, reflect the global trend of industrial detergents and irrigation return flows that alter the ionic balance of shallow aquifers, a process also observed in the intensive agricultural zones of the Mediterranean (Seckin et al., 2010).

Potassium: Potassium exhibited the most extreme variation in this study (CV: 169.61%), ranging from 0.35 to 93.8 mg/L. Because potassium is naturally limited by clay mineral fixation, research worldwide identifies levels above 10 mg/L as a definitive indicator of NPK fertilizer runoff or untreated sewage (Skowron et al., 2018). The localized “hotspots” in İnegöl reflect a similar vulnerability seen in Chinese and Indian fruit-growing regions, where high potassium serves as a marker for unregulated agricultural intensification (Vasanthavigar et al., 2010).

Calcium: In the study area, calcium concentrations varied between 1.96 and 194 mg/L (avg: 58.0 mg/L), remaining within the permitted limit of 200 mg/L. These parameters exhibited CVs values of approximately 48%, reflecting significant spatial heterogeneity. According to global hydrogeochemical models, the primary source is the dissolution of carbonate minerals (calcite and dolomite), which are common in mountainous recharge areas (Appelo and Postma, 2005). However, elevated levels near the İnegöl city center suggest supplemental urban-induced pressures, similar to groundwater patterns in European urban centers, where construction debris and domestic discharge influence water hardness.

Magnesium is an important parameter responsible for groundwater hardness. In this study, Mg concentrations ranged from 3.03 to 86.3 mg/L, with an average of 30.2 mg/L. The parameter exhibited a CV of 48.01%, reflecting significant spatial heterogeneity. This variation is primarily governed by the dissolution of magnesium-bearing carbonate rocks along the slopes of the Uludağ and Domaniç Mountains. However, the elevated levels found around the city of İnegöl indicate that natural geological sources are supplemented by urban-induced pressures such as unregulated domestic discharge.

Sulfate: In the current study, the sulfate levels ranged from 1.44 to 198.4 mg/L (CV:74.13%). International studies on textile heavy industrial zones, particularly in Southern India, have established a direct link between textile dyeing (using sodium sulfate) and localized sulfate anomalies in groundwater (Selvam et al., 2017). The İnegöl OSB results align with these global results, where industrial effluents overshadow natural sulfide oxidation processes.

Chloride: In the present study, the chloride values ranged from 0 to 214.1 mg/L (avg: 27.4 mg/L). This parameter exhibited a very high CV of 94.89%, which is a definitive indicator of anthropogenic pollution rather than a natural lithogenic origin. Globally, chloride is considered a conservative tracer of human impact; its high variability in the Bedre River valley matches observations in North American and Middle Eastern basins, where irrigation return flows and sewage leakage are the primary contributors (Machiwal et al., 2018).

Bicarbonate: This compound is formed as a result of the reaction of CO_2 with water in carbonate rocks, such as limestone and dolomite, and creates an alkaline environment in groundwater. In the study area, this value ranges from 97.6-641.9 mg/l (avg: 352.6 mg/L) with a low CV (26.12%), and bicarbonate is primarily controlled by natural processes. This stability is consistent with global hydrogeochemical observations, where the reaction of soil CO_2 with carbonate rocks provides a consistent baseline alkalinity for most temperate and semiarid aquifers (Appelo and Postma, 2005).

Total hardness: The total hardness, which can be temporary or permanent in nature, corresponds to the amount of dissolved calcium and magnesium in the water (Özşahin, 2013). Water passing through soil and rocks acts as an excellent solvent for calcium and magnesium, dissolving naturally occurring minerals and transporting them into groundwater. The total hardness ranged from 0 to 46.3 mg/L with a CV of 53.88%. The variation in hardness is directly linked to fluctuations in calcium and magnesium concentrations, reflecting the spatial differences in the solubility of minerals as water passes through the diverse lithology of the study area.

SAR: SAR is an important criterion for determining irrigation water quality. This is because an increase in SAR levels creates an unfavorable environment for plants, both by damaging the soil structure and reducing permeability and by causing crust-like structures to form on the soil surface after irrigation (Davraz and Ünver, 2014). In this study, the SAR was determined using the original formulation of Richards (1954). While all water wells in the study area fall under the category of irrigation water with “good” properties, the parameter exhibited spatial fluctuations, with relatively higher concentrations observed between Sipahi and Kozluca. The primary reason for this variation is the high spatial heterogeneity of the constituent cations, particularly sodium, which had a CV of 57.95%. This variability suggests that localized anthropogenic inputs, such as industrial discharge, influence the ionic balance and drive SAR levels in specific sectors of the plain.

%Na: Sodium percentage is another parameter used in classifying irrigation water quality. It is undesirable for the percentage of sodium in irrigation water to exceed the limit value (Islam et al., 2025). This is because excessive sodium content has harmful effects on plants and the soil (Davraz and Ünver, 2014). Following the original method proposed by Wilcox (1948), the water wells in the study area were generally classified between the “Very good” and “Usable” categories. However, the percentage of sodium increased significantly in the northeastern and eastern parts of the plain. This spatial trend is directly linked to the extreme variability of sodium and potassium concentrations in those areas, which exhibited CV values of 57.95% and 169.61%, respectively. These high variations are likely caused by intensive agricultural practices and the unregulated disposal of industrial waste, which introduces excess Na into the groundwater system and alters its suitability for long-term irrigation.

Groundwater Quality Indices

The results of the groundwater quality indices for samples taken from wells in the study area showed that the DWQI (74.8%) and IWQI (87.8%) were at an acceptable level (Excellent + Good) (Figure 3; Table 6). Twenty-seven wells for the DWQI and 13 wells for the IWQI had low-quality values (Table 6). Furthermore, it was determined that the remaining well No. 107 between Yeniceköy and İnegöl (DWQI: 115.12, IWQI: 97.83) had the most critical value (Figure 3; Table 7).

Table 6. Results of the distribution analysis of the water quality index and rating classes

WQI	Class	DWQI		IWQI	
		Number of wells	%	Number of wells	%
0 - 25	Excellent	5	4.7	14	13.1
26 - 50	Good	75	70.1	80	74.8
51 - 75	Poor	25	23.4	11	10.3
76 - 100	Very poor	1	0.9	2	1.9
101 ->	Not suitable	1	0.9	0	0.0

Table 7. Top ten wells with the highest index values

Well No	DWQI	IWQI	Class
107	115.12	97.83	Not suitable
88	93.28	79.83	Very poor
6	73.20	62.68	Poor
78	72.56	61.79	Poor
104	70.06	58.85	Poor
8	65.81	57.02	Poor
12	63.04	54.19	Poor
67	62.13	54.38	Poor
10	61.75	52.45	Poor
90	61.75	51.80	Poor

Discussion

The results indicate that the quality of groundwater in the study area is satisfactory, and there is a serious threat due to the increasing anthropogenic activities in the region. However, continued industrial expansion and agricultural intensification in the study area pose risks to long-term aquifer integrity. Integrated management strategies that combine source control, monitoring networks, and land-use planning are essential for preserving the groundwater quality for future generations (Foster and Chilton, 2003; Custodio, 2002; Islam et al., 2025).

The dominance of bicarbonate and strong calcium-magnesium correlation in the study area confirms

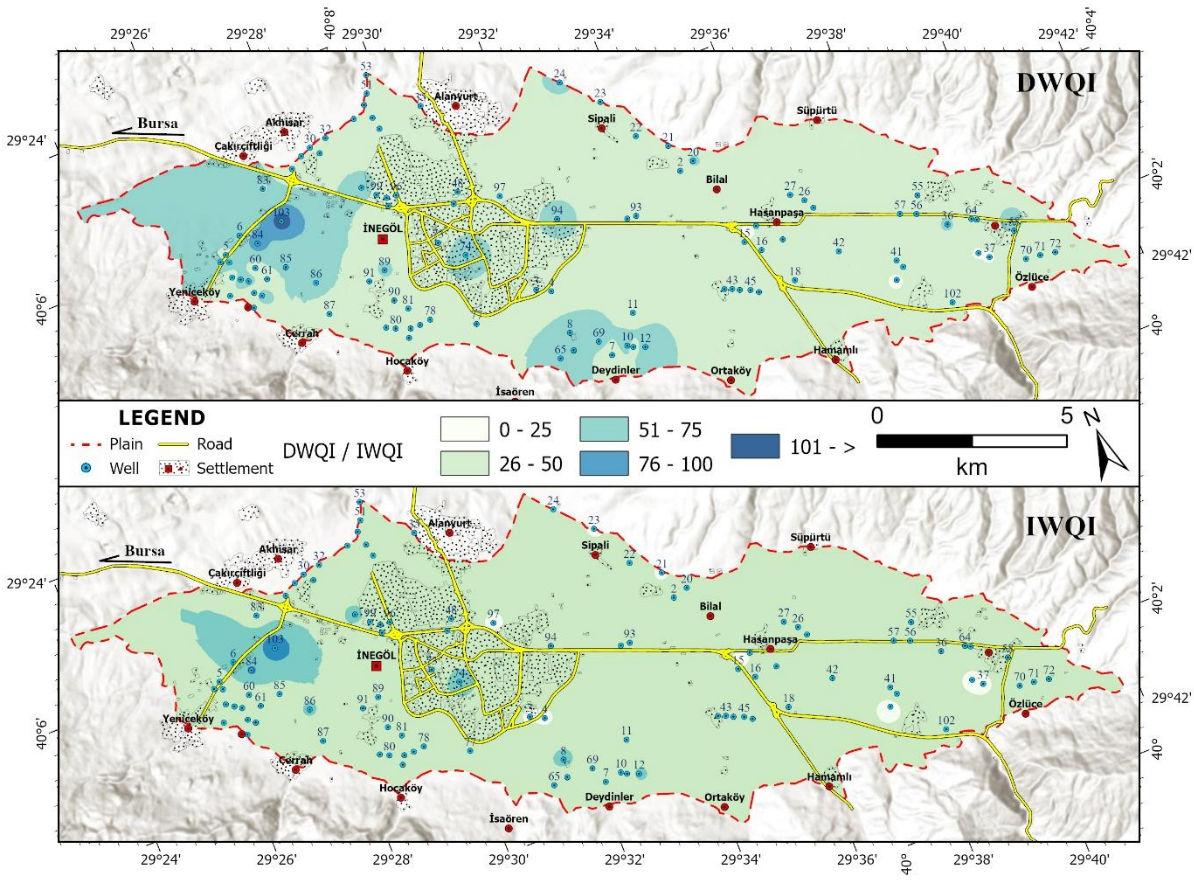

Figure 3. DWQI and IWQI distribution map of the study area

carbonate mineral dissolution as the primary hydrogeochemical process, consistent with global patterns in alluvial aquifers overlying carbonate bedrock (Appelo and Postma, 2005; Hem, 1985). This aligns with the conceptual model proposed by Edmunds and Smedley (2013) for semi-arid Mediterranean aquifers, where prolonged water-rock interaction under low recharge conditions drives progressive mineralization.

These results are consistent with those of previous studies in this area. İşlek (2012) reported that groundwater in the İnegöl Plain is affected by mineral deposits, domestic waste, and agricultural pollution, based on the chemical analysis results of well waters. Menteşe (2015) suggested that groundwater in the İnegöl Plain contains high levels of chemical substances and heavy metals. Davraz and Ünver (2014) determined that groundwater is more sensitive to pollution than surface water and that the largest pollutants in the İnegöl Plain are agricultural activities and solid-liquid waste. Dorak et al. (2019) reported that water quality has deteriorated and pollution levels have increased as a result of businesses with treatment plants in Bursa Province not operating their treatment plants regularly and illegal industrial establishments occupying fertile agricultural land in the plains discharging their wastewater uncontrollably. The CED (2017) stated that water pollution observed in Bursa Province is caused by industrial wastewater from industrial facilities, domestic wastewater from residential areas, leachate from unregulated solid waste disposal sites reaching water sources, and solid waste dumped into water basins. Dorak et al. (2019) emphasized that soil and water pollution in Bursa Province has reached significant levels due to the increase in both domestic and industrial waste associated with urbanization and industrialization.

The observed pH range (6.4-10.0) and alkaline shift in low-recharge zones reflect cation exchange processes, whereby calcium and magnesium are adsorbed onto clay minerals while Na is released into the solution (Appelo and Postma, 2005). This mechanism is well-documented in alluvial aquifers worldwide (Güler et al., 2002; Cloutier et al., 2008) and explains the spatial pattern of elevated pH and Na in the northern sector of the study area.

Localized enrichment of sodium, potassium, chloride, and sulfate near industrial facilities and the Bursa-İnegöl highway indicates anthropogenic contamination. Elevated potassium (CV: 169.61%) with 18 outliers strongly implicates agricultural fertilizer application, which is consistent with findings from intensively farmed alluvial plains in Europe (Sutton et al., 2011; Wick et al., 2012) and Asia (Xiao et al., 2014). Nitrogen-potassium-phosphorus (NPK) fertilizers are widely used in the İnegöl Plain for agricultural practices, and excess potassium leaching into groundwater is a well-established consequence of over-application (Spalding and Exner, 1993).

Sulfate enrichment (>150 mg/L) near textile and furniture manufacturing facilities suggests the discharge of industrial process water. Textile dyeing operations generate sulfate-rich effluents (Holkar et al., 2016; Kant, 2012), and inadequate wastewater treatment can lead to groundwater contamination in permeable aquifers (Chowdhury et al., 2015). Similar patterns have been documented in industrial regions of India (Karunanidhi et al., 2019), China (Wu et al., 2020), and Türkiye (Varol and Davraz, 2015).

The results of this study showed that the DWQI (74.8%) and IWQI (87.9%) were acceptable (excellent + good), indicating that the study area generally has satisfactory groundwater quality. However, localized degradation (poor + very poor) in 24.3% (DWQI) and 12.2% (IWQI) of the samples warrants concern. A comparison of these results with other Mediterranean alluvial aquifers reveals similar trends in groundwater unsuitability; for instance, unsuitable ratios were reported as 15% in the Konya Plain, Türkiye (Şener et al., 2017), 12% in the Thessaly Plain, Greece (Kazakis and Voudouris, 2015), and 18% in the Po Valley, Italy (Rotiroti et al., 2015). Previous studies on the İnegöl Plain have reported similar results. İşlek (2012) identified contamination from mineral deposits, domestic waste, and agricultural pollution based on chemical analysis of well water. Menteşe (2015) documented elevated levels of heavy metals and chemical substances, while Davraz and Ünver (2014) emphasized the vulnerability of groundwater to agricultural and solid-liquid waste pollution. Dorak et al. (2019) reported the progressive deterioration of water quality and increased pollution levels.

In this study, it was determined that the DWQI and IWQI rating classes in the vicinity of the Bursa-İnegöl highway are poor, very weak, and unsuitable. It was determined that water wells with the most critical values are also located in this region. Menteşe (2015) stated that high concentration levels were observed in water resources in the İnegöl Plain owing to urbanization and industrial activities. Uzun (2025) reported that, due to factors such as population growth and increasing demand in the İnegöl Plain, industrial activities, mining, technological developments, and the development of the transportation network, human activities in some areas around the Bursa-İnegol highway tend to reshape the topography, causing disruption in the dynamic functioning of the ecosystem.

The spatial concentration of degraded groundwater along the Bursa-İnegöl highway and in the southeastern industrial zone identifies priority areas for targeted monitoring and remediation. Regulatory interventions should focus on: (1) enforcing industrial wastewater treatment standards for textile and furniture facilities, (2) implementing best management practices for fertilizer application in agricultural zones, and (3) establishing buffer zones around high-quality wells to prevent contamination from highway runoff.

Continued industrial expansion and agricultural intensification in the study area pose a risk to long-term aquifer integrity. Integrated management strategies that combine source control, monitoring networks, and land-use planning are essential for preserving the groundwater quality for future generations (Custodio, 2002; Foster and Chilton, 2003).

This study was based on a dataset consisting of groundwater samples collected from 107 wells opened by the public and private sectors. However, long-term monitoring programs are necessary to assess whether groundwater quality studies are showing an increasing or decreasing trend. Therefore, future research should examine the spatiotemporal variation in groundwater in the study area (Dokou et al., 2015; Rahman et al., 2018). In addition, new contaminants that are increasingly being detected in groundwater worldwide (e.g., microplastics) should also be investigated (Lapworth et al., 2012; Kurwadkar et al., 2022). However, these data were not analyzed in the present study.

Conclusion

This study comprehensively evaluated the quality of groundwater in the İnegöl Plain by modeling its spatial distribution using GIS-based techniques. The findings indicate that while groundwater in the region generally maintains acceptable physical and chemical levels, increasing anthropogenic pressures and industrial expansion exert significant negative impacts on water quality. Specifically, the high spatial variability observed in parameters, such as pH, sodium, and potassium, serves as a diagnostic indicator of localized point-source pollution linked to the region's industrial and agricultural activities.

Assessments of groundwater quality indices confirm that the majority of aquifers remain suitable for both potable and agricultural applications. The DWQI yielded a "good" rating for 74.8% of the samples, while the IWQI categorized 87.8% of the study area as 'suitable.' However, a critical spatial trend was identified: the highest index values, indicating poor and unsuitable water quality, were concentrated along the Bursa-İnegöl highway and adjacent industrial zones. This clustering highlights the direct influence of transportation corridors and industrial discharge on surrounding subsurface resources.

The primary drivers of groundwater degradation in the İnegöl Plain include unregulated industrial effluents (specifically from the furniture and textile sectors), intensive chemical fertilization in agriculture, and inadequate domestic waste management. These anthropogenic activities introduce solid and liquid pollutants that bypass the natural filtration capacity of alluvial aquifers, posing a long-term threat to water security in the region.

It is important to acknowledge that this study has certain limitations regarding the age of the dataset utilized. Owing to regional data accessibility constraints and resource limitations, the analysis was based on available historical records. However, this situation does not diminish the value of the study; rather, these findings establish a critical historical baseline. Given that hydrogeochemical processes in complex alluvial systems often evolve over decadal scales, this study provides an essential benchmark for comparing future monitoring results and evaluating the long-term impacts of industrialization.

Consequently, while the İnegöl Plain's groundwater is currently largely viable, ongoing pressure from human activities necessitates urgent protective measures. Regular monitoring, stricter enforcement of wastewater discharge protocols, and the use of geospatial mapping as a decision support tool are vital for the sustainable management of these resources. Future research should prioritize real-time data collection and examine the integrated effects of seasonal variation and climate change on the groundwater quality characteristics of aquifers.

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Author Contribution

E.Ö.: Writing - original draft, Methodology, Data curation, Investigation. **E.T.:** Methodology, Investigation, Formal analysis, Data curation, Validation. **S.K.:** Writing - original draft, Data curation, Investigation.

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Conflict of Interest

No potential conflict of interest was reported by the authors.

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