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ORIGINAL ARTICLE

IWQ Index: A GIS-Integrated Technique to Assess Irrigation Water Quality

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Abstract The irrigation water quality and the associated hazards to soil characteristics and crop yield is often a complex phenomenon that involves the combined effect of many parameters. From a management point of view, it is sometimes necessary to analyze all related parameters as a combination rather than focusing on a single isolated parameter. With this objective in mind, a new GIS-integrated tool is proposed in this study to evaluate the quality of irrigation waters with regards to potential soil and crop problems. The proposed procedure is mainly an index method that utilizes five hazard groups: (a) salinity hazard, (b) infiltration and permeability hazard, (c) specific ion toxicity, (d) trace element toxicity; and, (e) miscellaneous impacts on sensitive crops. A linear combination of these groups is formulated to form the so-called IWQ index, which is a technique that could be used to classify irrigation waters with respect to three suitability classes. The proposed technique is applied to assess the irrigation water quality of the Simav Plain located in western Anatolia, Turkey. The Simav application is implemented by using a GIS database developed for the plain. Based on the results of this application, the general groundwater quality in the surfacial aquifer is found to be fairly good and the aquifer waters are mostly suitable for irrigation purposes.

Keywords Irrigation water quality · Salinity hazard · Infiltration hazard · Specific ion toxicity · Trace element toxicity · Miscellaneous effects · Index method · GIS · Simav-Turkey

1 Introduction

It has been known for years that the quality of irrigation water directly influences the quality of the soil and the crops grown on this soil. In the last century, the demand for agricultural land and products has grown rapidly as a function of population growth. In addition, experts from all disciplines have agreed that factors such as urbanization, industrialization, poor land management and environmental pollution imposed additional stress on agricultural production. All of these factors have quickly become responsible for the decrease in the amount of land available for agriculture and for the reduction in the quantity and the quality of water to irrigate these lands. A dramatic example for this soil–water quality interaction phenomenon is the salinity problem that is widely experienced in many parts of the world where about 10 million hectares of agricultural land is lost annually (Tanji, 1990; Kwiatkowski, Marciak, Wentz, & King, 1995). As a consequence, effective use of both the agricultural land and the irrigation water has become an indispensable component, if not the primary objective, of many agricultural development and management plans.

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In the last century, another detrimental consequence of the above mentioned stress factors has been experienced in the quantity and quality of surface waters. Invaluable surface water resources have either been over consumed to their capacity and/or been polluted to such levels that they could no longer be used not only in direct human consumption but also in agricultural irrigation. In many parts of the world, this situation has led people depend more on groundwater resources and has inevitably resulted in increased demands on the quantity and quality of groundwater. It has now become clear that this extra burden on groundwater had its own costs such as rapid decline in economically consumable groundwater levels, salt water intrusion in coastal aquifers and infiltration of polluted surface waters into groundwater.

The utilization of degraded quality waters in irrigation has been the main cause for the deterioration of the quality of soils and the agricultural crops grown on such soils (Wilcox, 1948; Ayers, 1977; Ayers and Westcot, 1985). This degradation has mainly been attributed to the accumulation of various ions in the soil mass as a result of the presence of such ions in irrigation waters in elevated concentrations. While some of these ions and elements naturally appeared in water (i.e., due to interactions with geological formations), many originated from major anthropological activities. Regardless of the cause, the increase in the concentrations of such ions degraded the quality of irrigation waters and created vital problems in agricultural production.

Based on this current situation, water quality management has become an important tool to guarantee the required amount of agricultural production for current needs and to maintain the sustainability of the land for future generations. Motivated by this necessity, decision makers have asked the experts to provide non-technical tools to help them come up with better decisions. The so-called index techniques and water quality mapping have been developed as a result of this need. Although initially formulated to assess the quality of drinking waters, it is believed that a similar logic could easily be applied for assessing the quality of irrigation waters as the only difference between the two is how water is ultimately consumed.

The irrigation water quality is mainly assessed as a function of the level of certain quality parameters. These parameters are generally associated with a particular irrigation problem or some specific hazard that their presences are likely to create. In general, the quality of an irrigation water resource is associated with its (a) salinity hazard, (b) infiltration or permeability hazard, (c) specific ion toxicity, (d) trace element toxicity; and, (e) various miscellaneous effects to susceptible crops. However, it is important to note that these hazards or negative impacts could sometimes occur simultaneously, thus making their relative significance more difficult to assess. Furthermore, spatial distributions of other factors such as soil type and crop pattern bring in additional complexity to the problem. Therefore, it is clear that all of these parameters must be involved in some way to better assess irrigation water quality.

Based on this motivation, a GIS-based index method is developed in this study as a general assessment tool with particular emphasis on the spatial variations of all related physicochemical quality parameters. The results of the technique are evaluated based on the degree of the restriction (i.e., none, slight to moderate and severe) on the use of irrigation water. The integration of the geographic information system (GIS) platform to the assessment procedure not only allows the decision maker to create parameter maps for easy visual interpretation but also makes the overall analysis more sound, objective and simple.

The developed technique is then applied to assess the quality of groundwater in Simav Plain located in Kutahya province of Turkey where it is used as the primary source of irrigation water. Accordingly, a database is created for the project area by collecting data from a total of 26 wells drilled in the surfacial aquifer. This GIS-integrated database is then used to create input data layers of the developed tool including the salinity hazard, the infiltration and permeability hazard, the specific ion toxicity, the trace element toxicity and the miscellaneous effects to sensitive crops. Finally, a composite irrigation water quality map is obtained for the Simav Plain based on the proposed index technique. The results of this case study are further used to understand the current status of groundwater quality in the plain where it is also used as a drinking water resource.

2 Irrigation Water Quality

The quality of irrigation water is highly variable depending upon both the type and the quantity of the salts dissolved in it. These salts originate from natural (i.e., weathering of rocks and soil) and anthropological (i.e., domestic and industrial discharges) sources and once introduced, they follow the flow path of the water. The irrigated soils and the crops grown on such soils are considered to be ultimate sinks for these salts and minerals as a result of evaporation and crop consumption. In general, the problems associated with the soil's salt content increase as the total salt content of the irrigation water increases. Therefore, the irrigation water quality should be considered as an important tool in the sustainable management of the soil resources and the agricultural production (Wilcox, 1955).

It is commonly accepted that the problems originating from irrigation water quality vary in type and severity as a function of numerous factors including the type of the soil and the crop, the climate of the area as well as the farmer who utilizes the water. Nevertheless, there is now a common understanding that these problems can be categorized into the following major groups: (a) salinity hazard, (b) infiltration and permeability problems, (c) toxicity hazards; and, (d) miscellaneous problems (Ayers & Westcot, 1985). The toxicity hazards can further be grouped into problems associated with specific ions as well as hazards related to the presence of trace elements and heavy metals.

2.1 Salinity hazard

Salinity hazard occurs when salts start to accumulate in the crop root zone reducing the amount of water available to the roots. This reduced water availability sometimes reaches to such levels that the crop yield is adversely affected. These salts often originate from dissolved minerals in the applied irrigation water or from a high saline water table. The reductions in crop yield occur when the salt content of the root zone reaches to the extent that the crop is no longer able to extract sufficient water from the salty soil. When this water stress is prolonged, plant slows its growth and drought-like symptoms start to develop (Ayers & Westcot, 1985). Unless the soil is leached with low salt content water, the salinization of the soil is an irreversible process that makes agricultural lands unusable.

Being the most influential water quality guideline on crop productivity, the extent of salinity hazard could be measured by the ability of water to conduct an electric current. Since conductance is a strong function of the total dissolved ionic solids, either an electrical conductivity (EC) measurement or a total dissolved solids (TDS) analysis could be used in measuring the salinity of water. Although these terms are comparable and quantify the amount of salts dissolved in water, TDS is a direct measure of dissolved solids and EC is an indirect measure of ions by an electrode.

In general, the amount of water available to the crop gets lower when the electrical conductivity is higher. Under such circumstances, the soil appears to be wet but the crop experiences the so-called physiological drought. Since plants can only transpire 'pure' water, the usable portion of water by plants decreases dramatically as conductivity increases. Usually, waters with EC values of below 700 μS/cm are considered to be good quality irrigation waters. The classification of irrigation water quality based upon its EC value is presented in Table I.

2.2 Permeability and infiltration hazard

Although the infiltration rate of water into soil is a function of many parameters including the quality of the irrigation water and the soil factors such as structure, compaction and the organic content, the permeability and infiltration hazard typically occurs when high sodium ions decrease the rate at which irrigation water enters the soil's lower layers. The reduced infiltration rate starts to show negative impacts when water cannot infiltrate to the roots of the crop to the extent that the crop requires. Hence, these salts start to accumulate at the soil surface. When the crop is not able to extract the required amount of water from the soil, it is not possible to maintain an acceptable yield and the agricultural production is reduced.

The two most common water quality factors that influence the normal rate of infiltration of water are the salinity of water and the relative concentrations of sodium, magnesium and calcium ions in water that is also known as the sodium adsorption ratio (SAR). The SAR value of irrigation water quantifies the relative proportions of sodium (Na^+) to calcium (Ca^{++}) and magnesium (Mg^{++}) and is computed as:

$$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{[\mathrm{Ca}^{++}]+[\mathrm{Mg}^{++}]}{2}}} \qquad (1)$$

where $[Na^+]$, $[Ca^{++}]$ and $[Mg^{++}]$ are defined as the concentrations of sodium, calcium and magnesium ions in water, respectively (Ayers & Westcot, 1985). In this equation, the concentrations are expressed as milliequivalents per liter and are computed by dividing the

Table I Irrigation water quality criteria classification (Ayers & Westcot, 1985)

Potential irrigation problem		Unit	Degree of restriction on use		
			None	Slight to moderate	Severe
Salinity (effects crop water availability)	EC	µS/cm	< 700	700–3,000	> 3,000
	TDS	mg/l	< 450	450–2,000	> 2,000
Permeability (effects infiltration rate of water into soil)	SAR = 0–3	and EC=	> 700	700–200	< 200
	SAR = 3–6		> 1,200	1,200–300	< 300
	SAR = 6–12		> 1,900	1,900–500	< 500
	SAR = 12–20		> 2,900	2,900–1,300	< 1,300
	SAR = 20–40		> 5000	5,000–2,900	< 2,900
Specific ion toxicity (effects sensitive crops)	Sodium[1]	SAR	< 3.0	3.0–9.0	> 9.0
	Chloride[1]	mg/l	< 140	140–350	> 350
	Boron	mg/l	< 0.7	0.7–3.0	> 3.0
Miscellaneous effects (effects susceptible crops)	Nitrate–nitrogen	mg/l	< 5	5–30	> 30
	Bicarbonate	mg/l	< 90	90–500	> 500
	pH	–	Normal range 6.5–8.4		

[1] Surface irrigation.

aqueous concentration of the corresponding ion expressed in milligrams per liter by the product of its atomic weight and ionic charge.

Accordingly, a combined EC-SAR criterion is used to assess the potential infiltration hazard that might develop in a soil. While a low salinity water with high SAR values has a severe infiltration hazard, a high salinity water with low SAR values does not experience any infiltration problem.

As both salinity and SAR operate at the same time, the levels of sodium ions in water are the determining parameters for potential infiltration hazards. It is also important to note that the these hazards typically occur in the first few centimeters of the top soil and is strongly linked to the structural stability of the surface soil and its low calcium content relative to that of sodium (Ayers & Westcot, 1985). It has been found that when a soil is irrigated with waters of high sodium concentrations, a high sodium surface is reported to develop which in turn weakens the soil structure. The soil aggregates and then disperses to smaller particles and clogs its pores. Another important parameter is the soil's clay content. The high SAR values have a negative impact on soil structure due to the dispersion of clay particles. The classification of irrigation water quality based upon its infiltration hazard is presented in Table I.

2.3 Specific ion toxicity

Certain ions such as sodium, chloride and boron cause toxicity problems for plants when they are found in elevated concentrations in water or in soil. When these ions are taken up by the plant and accumulate to concentrations high enough to cause crop damage or yield reduction, they are considered to be toxic. The level of toxicity is specific to plant type and uptake rate. The permanent, perennial type crops are more sensitive to this type of toxicity when compared to the annual crops. It is also known that ion toxicity is usually accompanied by other problems such as salinity and infiltration hazards (Ayers & Westcot, 1985).

2.3.1 Sodium

The detection of sodium toxicity is relatively difficult compared to the toxicity of other ions. Typical toxicity symptoms on the plant are leaf burn, scorch and dead tissue along the outside edges of leafs in contrast to symptoms of chloride toxicity which normally occur initially at the extreme leaf tip (Ayers & Westcot, 1985). As discussed in Section 2.2, the sodium ion also causes hazards in the soil structure creating reduced permeability and water infiltration problems. In addition, calcium and magnesium ions are replaced by sodium ion creating an increase in soil's sodium content (Todd & Mays, 2004).

While EC is an assessment of all soluble salts in water, sodium hazard is generally defined separately due to sodium's specific detrimental effects on soil physical properties and plant survival. Thus, the sodium hazard is expressed as SAR, which defines the relative proportions of sodium to calcium and magnesium ions in a water sample. In general, waters with SAR values of below 3 are considered to be good quality irrigation waters. The classification of irrigation water quality based upon its SAR value is presented in Table I.

2.3.2 Chloride

Chloride is another ion commonly found in irrigation waters. Although it is essential to crops at low concentrations, it can cause toxicity to sensitive crops at higher levels. Its toxic effects are immediately seen as leaf burns or leaf tissue deaths. Normally, injury to plant occurs first at the leaf tips and progresses from the tip back along the edges as severity increases. In excessive cases, early leaf drop or defoliation occurs (Ayers & Westcot, 1985). In general, waters with chloride values of below 140 mg/l are considered to be good quality irrigation waters. The classification of irrigation water quality based upon its chloride value is presented in Table I.

2.3.3 Boron

Boron is an element that is essential for plant growth when found in soil and water in low concentrations but is considered to be toxic when its concentration exceeds certain levels (Eaton, 1935; Todd & Mays, 2004). Boron toxicity symptoms normally appear first on older leaves as a yellowing, spotting, or drying of leaf tissue at the tips and edges. Drying often progresses toward the center between the veins as more boron accumulates with time (Ayers & Westcot, 1985). In general, boron toxicity starts to develop in sensitive crops above 0.7 mg/l. The classification of irrigation water quality based upon its boron value is presented in Table I.

2.4 Trace element toxicity

The environmental and climatologic factors strongly influence the soil and subsurface water chemistry. These factors could increase the dissolution of numerous minerals in water and could cause toxic effects (Evangelou, 1998). The presence of some trace elements and various heavy metals in the irrigation water are known to be responsible for soil pollution and are particularly important for irrigation water quality due to some of their unique properties including their resistance to biodegradation and thermodegradation (Bohn, McNeal, & C'Connor, 2001).

Unlike other potential pollutants that visibly build-up on soils, trace elements and heavy metals can accumulate unnoticed to extremely high toxic concentrations before affecting plant, animal and human life. When their effects on plants are considered, one could observe that they would ultimately be taken up by the plant's root system and would later be accumulated within the plant's stems and leaves. This accumulation adversely effects the plant's growth and yield, and could sometimes cause its death. In addition, the increased concentrations of these minerals in upper layers of the soil would also be transported to lower layers and eventually to groundwater table with the infiltrating water; significantly degrading the groundwater quality.

It has been observed that elements such as arsenic, cadmium, copper, lead, manganese, mercury, nickel and zinc could easily accumulate in crops irrigated with waters that are contaminated by industrial discharges (Ray, Barman, & Khan, 1989). Particularly, arsenic is considered to be one of the most toxic elements for crops. It has been documented that arsenic could be absorbed by various crops at different rates. Particularly, it could accumulate more easily in the leaves of the crops and could be extremely toxic to humans when the leaves of such crops are consumed (Farid, Roy, Hossain, & Sen, 2003). In a study conducted on crops grown in the Mediterranean basin, it has been found out that copper, manganese and zinc have accumulated in the leaves and the stems of the crop at very high levels and has become toxic to the plant itself (Kalavrouziotis & Drakatos, 2002). In this regard, the accumulation of such elements in crops causes plant toxicity and product loss. In another study conducted in Zimbabwe, it has been found out that unless the annual heavy metal loading rates are controlled, metals such as copper, zinc, cadmium, nickel, chromium and lead would exceed their permitted limits in soils within a maximum of 60 year time frame (Mapanda, Mangwayna, Nyamangara, & Giller, 2005). It was further concluded that the use of wastewater in irrigation have enriched the soils with heavy metals to concentrations that may pose potential environmental and health risks in the long-term (Mapanda et al., 2005).

Unfortunately, the duration of contamination by heavy metals might persist for hundreds or thousands of years even after their addition to soils has been terminated. The research has shown that the time required for cadmium, copper and lead to reach half their concentrations in soil was found to be 15–1,100, 310–1,500 and 740–5,900 years, respectively, depending on soil type and physiochemical parameters (Alloway & Ayres, 1993). Hence, it is important to continuously monitor the levels of trace elements and heavy metals within soil structure, particularly when irrigation water contains high concentrations. However, it is also important to note that such elements could as well be found in waters where there are no anthropological activities (i.e., an uncontrolled domestic or industrial discharge) that influence their quality. In many circumstances, these elements might originate from the geological formations and mining sites, and could quickly dissolve in surface and subsurface waters used in irrigation purposes.

Based on these considerations, the trace element content of irrigation waters should be carefully reviewed during the assessment of an irrigation water resource. Although there are no universally accepted sensitivity levels, Ayers and Westcot (1985) and Crook (1996) have provided concentration limits for long and short term use of irrigation waters containing these elements. These limits are given in Table II.

Table II Recommended limits for trace elements in irrigation waters (Ayers & Westcot, 1985; Crook, 1996)

Constituent	Long-term use (mg/l)	Short-term use (mg/l)
Aluminum (Al)	5.0	20
Arsenic (As)	0.1	2.0
Beryllium (Be)	0.1	0.5
Cadmium (Cd)	0.01	0.05
Chromium (Cr)	0.1	1.0
Cobalt (Co)	0.05	5.0
Copper (Cu)	0.2	5.0
Fluoride (F)	1.0	15.0
Iron (Fe)	5.0	20.0
Lead (Pb)	5.0	10.0
Lithium (Li)	2.5	2.5
Manganese (Mn)	0.2	10.0
Molybdenum (Mo)	0.01	0.05
Nickel (Ni)	0.2	2.0
Selenium (Se)	0.02	0.02
Vanadium (V)	0.1	1.0
Zinc (Zn)	2.0	10.0

2.5 Miscellaneous effects

In addition to the hazards and effects discussed in the previous sections, there are additional parameters, presence of which must be assessed carefully in irrigation waters. These are considered within the scope of miscellaneous effects to sensitive crops and include the pH value of the water as well as the concentrations of bicarbonate ion and nitrate–nitrogen.

2.5.1 pH

The pH value of irrigation water changes as a function of several parameters including contamination from various pollution sources and acid rains. The pH value influences the carbonate equilibrium, heavy metal content and the relative ratio of nitrogen components, which in turn influences soil quality and plant growth. In acidic waters, calcium, magnesium and aluminum are not absorbed properly by plants. On the other hand, basic waters provide a better environment for plant's uptake of several metals and nutrients. However, basic waters are also responsible for calcium carbonate accumulation that influences the physical structure of water. In general, the ideal pH values of irrigation waters range from 7.0 to 8.0. The classification of irrigation water quality based upon its pH value is presented in Table I.

2.5.2 Bicarbonate

Alkalinity is a measure of the capacity of water to neutralize an added acid. Being the major component of alkalinity, carbonate and bicarbonate ions are generally responsible for high pH values (i.e., above 8.5) of water. Elevated levels of carbonates cause calcium and magnesium ions to form insoluble minerals leaving sodium as the dominant ion in solution. Hence, it is indirectly responsible from the hazards that high sodium concentrations cause on the irrigated crops and the soil. Thus, it is possible to conclude that highly alkaline irrigation waters could intensify sodic soil conditions. In such cases, it is recommended to calculate an adjusted SAR to reflect the increased sodium hazard. In general, the bicarbonate concentration values of below 90 mg/l are considered to be ideal for irrigation. The classification of irrigation water quality based upon its pH value is presented in Table I.

2.5.3 Nitrate–Nitrogen

It is well known that nitrate is the primary source of nitrogen to most plants and is commonly used as a fertilizer (Fedkiw, 1991). Nevertheless, excessive amounts of nitrate could result in the reduction in yield or quality of the crop as a result of delayed crop maturity, untimely growth or unsightly deposits on the fruit or foliage. However, many of these problems can usually be overcome by proper fertilizer and irrigation management. Furthermore, nitrate application to soils should be done with utmost care since it could easily cause nitrate pollution in local groundwater resources. In general, the ideal nitrate–nitrogen values of the irrigation waters should be below 5 mg/l. The classification of irrigation water quality based upon its nitrate–nitrogen value is presented in Table I.

3 Mapping Irrigation Water Quality

The requirements for irrigation water quality could differ from one field to the other depending on the cultivated crop pattern as well as the regional soil and climatologic conditions. In this regard, irrigation water quality mapping is considered to be a valuable instrument for the spatially distributed assessments of individual quality parameters. Accordingly, GIS provides an important platform for visualizing such maps and making comparative evaluations. However, in addition to individual assessments, a critical phase of the quality management procedure is to collectively evaluate all parameters mentioned in the previous section. For such a combined assessment, a GIS-integrated index technique becomes a necessity.

In the past, index techniques were commonly used to assess water quality. One of the earliest examples of such techniques included the research conducted by Horton (1965) where he developed an indexing method for rating the quality of water resources. Later, Aller, Bennett, Lehr, Petty, and Hackett (1987) have developed the popular DRASTIC index to compute vulnerability of a groundwater aquifer to surface pollution. Vollenweider, Giovanardi, Montanari, and Rinaldi (1988) have used a generalized water quality index to characterize the trophic conditions of marine coastal waters with special reference to the northwestern Adriatic Sea. More recently, Mohan, Nithila, and Reddy (1996) and Prasad and Bose (2001) have also formulated index methods to assess the heavy metal contents of water resources. Nagels, Davies-Colley, and Smith (2001) have developed a similar method to analyze the quality of contact recreation waters. Moreover, Fernandez, Chescheir, Skaggs, and Amatya (2002) have created a lumped parameter water quality model with complete GIS integration that is based on the same fundamentals. Finally, the study by Debels, Figueroa, Urrutia, Barra, and Niell (2005) has used a modified water quality index that is composed of physicochemical parameters for evaluating the quality status of a river in Central Chile.

Despite the large number of studies regarding general water quality index techniques, no complete assessment tool has been found in the literature that incorporates all five crucial aspects of irrigational water quality analysis discussed previously. Furthermore, it has also been realized that GIS-integration of irrigation water quality assessment has not been done to the extent that this study intends to perform. Thus, an *I*rrigation *W*ater *Q*uality (IWQ) index is developed in this study to provide an easy-to-use tool that could help analyze the overall quality of irrigation water. The technique also allows the decision maker perform a spatially distributed analysis from a broader perspective.

4 The Proposed Methodology

The proposed IWQ index is a GIS-integrated method that is based on the linear combination of the five different groups of irrigation water quality parameters that have potential negative impacts or hazards on soil quality and crop yield. In this technique, all five groups are simultaneously included in the analysis and are combined to form a single index value, which is then assessed to determine the suitability of the irrigation water. The water quality parameters from these groups are selected based on the guidelines presented by Ayers and Westcot (1985) given in Tables I and II. These parameters not only best characterize the associated hazard but also combine with others to form a general pattern of water quality for the particular resource. Furthermore, these parameters are arranged such that the results obtained from this tool would make sense to a non-technical decision maker and that he/she could use the method without difficulty.

Table III Classification for IWQ index parameters

Hazard	Weight	Parameter	Range	Rating	Suitability
Salinity hazard	5	Electrical conductivity (μS/cm)	$EC < 700$	3	High
			$700 \leq EC \leq 3{,}000$	2	Medium
			$EC > 3{,}000$	1	Low
Infiltration and permeability hazard	4	See Table IV for details			
Specific ion toxicity	3	Sodium adsorption ratio (-)	$SAR < 3.0$	3	High
			$3.0 \leq SAR \leq 9.0$	2	Medium
			$SAR > 9.0$	1	Low
		Boron (mg/l)	$B < 0.7$	3	High
			$0.7 \leq B \leq 3.0$	2	Medium
			$B > 3.0$	1	Low
		Chloride (mg/l)	$CI < 140$	3	High
			$140 \leq CI \leq 350$	2	Medium
			$CI > 350$	1	Low
Trace element toxicity	2	See Table V for details			
Miscellaneous effects to sensitive cops	1	Nitrate Nitrogen (mg/l)	$NO_3-N < 5.0$	3	High
			$5.0 \leq NO_3-N \leq 30.0$	2	Medium
			$NO_3-N > 30.0$	1	Low
		Bicarbonate (mg/l)	$HCO_3 < 90$	3	High
			$90 \leq HCO_3 \leq 500$	2	Medium
			$HCO_3 > 500$	1	Low
		pH	$7.0 \leq pH \leq 8.0$	3	High
			$6.5 \leq pH < 7.0$ and $8.0 < pH \leq 8.5$	2	Medium
			$pH < 6.5$ or $pH > 8.5$	1	Low

The proposed index uses the electrical conductivity parameter to represent the salinity hazard. This parameter could easily be measured in field conditions and does not require lengthy laboratory procedures. Furthermore, it is one of the required parameters for determining the infiltration and permeability hazards together with SAR. Even if TDS had been selected for quantifying the salinity hazard, the EC values would have been needed for assessing the infiltration hazard. Accordingly, it is more appropriate to use EC in determining both the salinity and the infiltration hazards. When EC is assessed alone to represent the salinity hazard, high values correspond to high salinity waters that must be restricted or used with caution. On the other hand, it is advantageous to have high EC values in high SAR irrigation waters when EC and SAR are assessed together to represent the infiltration hazard. As seen from Table I, high EC values act to counter balance the infiltration hazard of SAR in such situations.

IWQ index incorporates the specific ion toxicity by including boron, chloride and sodium ions. A linear combination of these parameters is included in the index value. In this group, boron and chloride ions are assessed based on their concentration values whereas sodium toxicity is evaluated as SAR, which also necessitates the measurement of the concentrations of magnesium and calcium. The index also incorporates the trace element toxicity by including the parameters depicted in Table II. A weighted average of the trace

Table IV Classification for infiltration and permeability hazard

	SAR					Rating	Suitability
	< 3	3–6	6–12	12–20	> 20		
EC	> 700	> 1,200	> 1,900	> 2,900	> 5,000	3	High
	700–200	1,200–300	1,900–500	2,900–1,300	5,000–2,900	2	Medium
	< 200	< 300	< 500	< 1,300	< 2,900	1	Low

Table V Classification for trace element toxicity

Factor	Range	Rating	Suitability
Aluminum (mg/l)	$Al < 5.0$	3	High
	$5.0 \leq Al \leq 20.0$	2	Medium
	$Al > 20.0$	1	Low
Arsenic (mg/l)	$As < 0.1$	3	High
	$0.1 \leq As \leq 2.0$	2	Medium
	$As > 2.0$	1	Low
Beryllium (mg/l)	$Be < 0.1$	3	High
	$0.1 \leq Be \leq 0.5$	2	Medium
	$Be > 0.5$	1	Low
Cadmium (mg/l)	$Cd < 0.01$	3	High
	$0.01 \leq Cd \leq 0.05$	2	Medium
	$Cd > 0.05$	1	Low
Chromium (mg/l)	$Cr < 0.1$	3	High
	$0.1 \leq Cr \leq 1.0$	2	Medium
	$Cr > 1.0$	1	Low
Cobalt (mg/l)	$Co < 0.05$	3	High
	$0.05 \leq Co \leq 5.0$	2	Medium
	$Co > 5.0$	1	Low
Copper (mg/l)	$Cu < 0.2$	3	High
	$0.2 \leq Cu \leq 5.0$	2	Medium
	$Cu > 5.0$	1	Low
Fluoride (mg/l)	$F < 1.0$	3	High
	$1.0 \leq F \leq 15.0$	2	Medium
	$F > 15.0$	1	Low
Iron (mg/l)	$Fe < 5.0$	3	High
	$5.0 \leq Fe \leq 20.0$	2	Medium
	$Fe > 20.0$	1	Low
Lead (mg/l)	$Pb < 5.0$	3	High
	$5.0 \leq Pb \leq 10.0$	2	Medium
	$Pb > 10.0$	1	Low
Lithium (mg/l)	$Li < 2.5$	3	High
	$2.5 \leq Li \leq 5.0$	2	Medium
	$Li > 5.0$	1	Low
Manganese (mg/l)	$Mn < 0.2$	3	High
	$0.2 \leq Mn \leq 10.0$	2	Medium
	$Mn > 10.0$	1	Low
Molybdenum (mg/l)	$Mo < 0.01$	3	High
	$0.01 \leq Mo \leq 0.05$	2	Medium
	$Mo > 0.05$	1	Low
Nickel (mg/l)	$Ni < 0.2$	3	High
	$0.2 \leq Ni \leq 2.0$	2	Medium
	$Ni > 2.0$	1	Low
Selenium (mg/l)	$Se < 0.01$	3	High
	$0.01 \leq Se \leq 0.02$	2	Medium
	$Se > 0.02$	1	Low
Vanadium (mg/l)	$V < 0.1$	3	High
	$0.1 \leq V \leq 1.0$	2	Medium
	$V > 1.0$	1	Low
Zinc (mg/l)	$Zn < 2$	3	High
	$2 \leq Zn \leq 10$	2	Medium
	$Zn > 10.0$	1	Low

Table VI Irrigation water quality (IWQ) index

IWQ index	Suitability of water for irrigation
< 22	Low
22–37	Medium
> 37	High

elements is used since some of these parameters might not be measured at all locations. However, the user should be aware of the fact that such limitations in data might create results that would fail to represent the actual field conditions for several parameters and might eventually result in errors in the overall suitability assessment. Despite the fact that the index computation is designed to allow the user to incorporate only the measured elements without causing any error in the analysis due to the non-measured ones, measuring all the trace metals given in Table II should be the primary objective of any suitability study to be conducted by the proposed technique. Finally, the index integrates the influence of miscellaneous effects to sensitive crops by including a linear combination of nitrate–nitrogen, bicarbonate and pH.

In the proposed technique, each one of these parameters are given a weighing coefficient (Table III and IV) from 1 to 5 such that the most and the least important groups in irrigation water quality are given the highest (5) and lowest (1) points. As the salinity hazard is considered to be the most important factor in irrigation water quality assessment, it is given the highest priority. On the other hand, the miscellaneous effects to sensitive crops are generally considered as the least important factor influencing the irrigation water quality. Between these two extremes, the infiltration and permeability hazard, specific ion toxicity and trace element toxicity are rated in decreasing order of significance for irrigation water quality. Although one can argue that these factors might show radical differences in different geographical settings with distinct soil conditions and different crop patterns, it is believed that the importance classification given in Table III could be used with safety for a typical agricultural pattern as a general quality assessment tool. For conditions that deviate from the generalization presented in this study, the decision maker could easily modify the procedure and

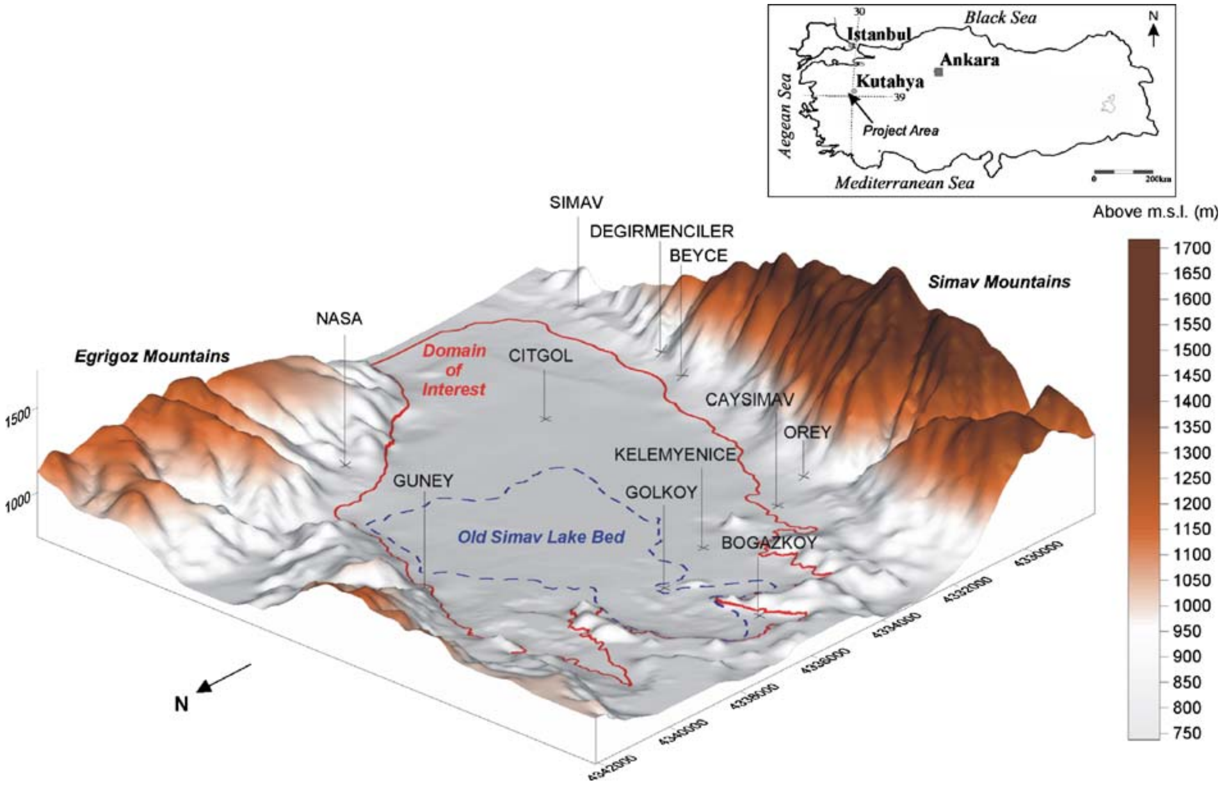

Figure 1 Location map of the study area.

use alternate weighing coefficients for the five parameter groups introduced in this work. In addition to the weighing coefficients, the technique also assigns rating factors for each parameter as shown in Table III and IV. The proposed IWQ index is then calculated as:

$$\text{IWQ Index} = \sum_{i=1}^{5} G_i \tag{2}$$

where i is an incremental index and G represents the contribution of each one of the five hazard categories that are important to assess the quality of an irrigation water resource. The first category is the salinity hazard that is represented by the EC value of the water and is formulated as:

$$G_1 = w_1 r_1 \tag{3}$$

where w is the weight value of this hazard group and r is the rating value of the parameter as given in Table III. The second category is the infiltration and permeability hazard that is represented by EC-SAR combination and is formulated as:

$$G_2 = w_2 r_2 \tag{4}$$

where w is the weight value of this hazard group and r is the rating value of the parameter as given in Table IV. The third category is the specific ion toxicity that is represented by SAR, chloride and boron ions in the water and is formulated as a weighted average of the three ions:

$$G_3 = \frac{w_3}{3} \sum_{j=1}^{3} r_j \tag{5}$$

where j is an incremental index, w is the weight value of this group as given in Table III and r is the rating value of each parameter as given in Table IV. The fourth category is the trace element toxicity that is represented by the elements given in Table II and is

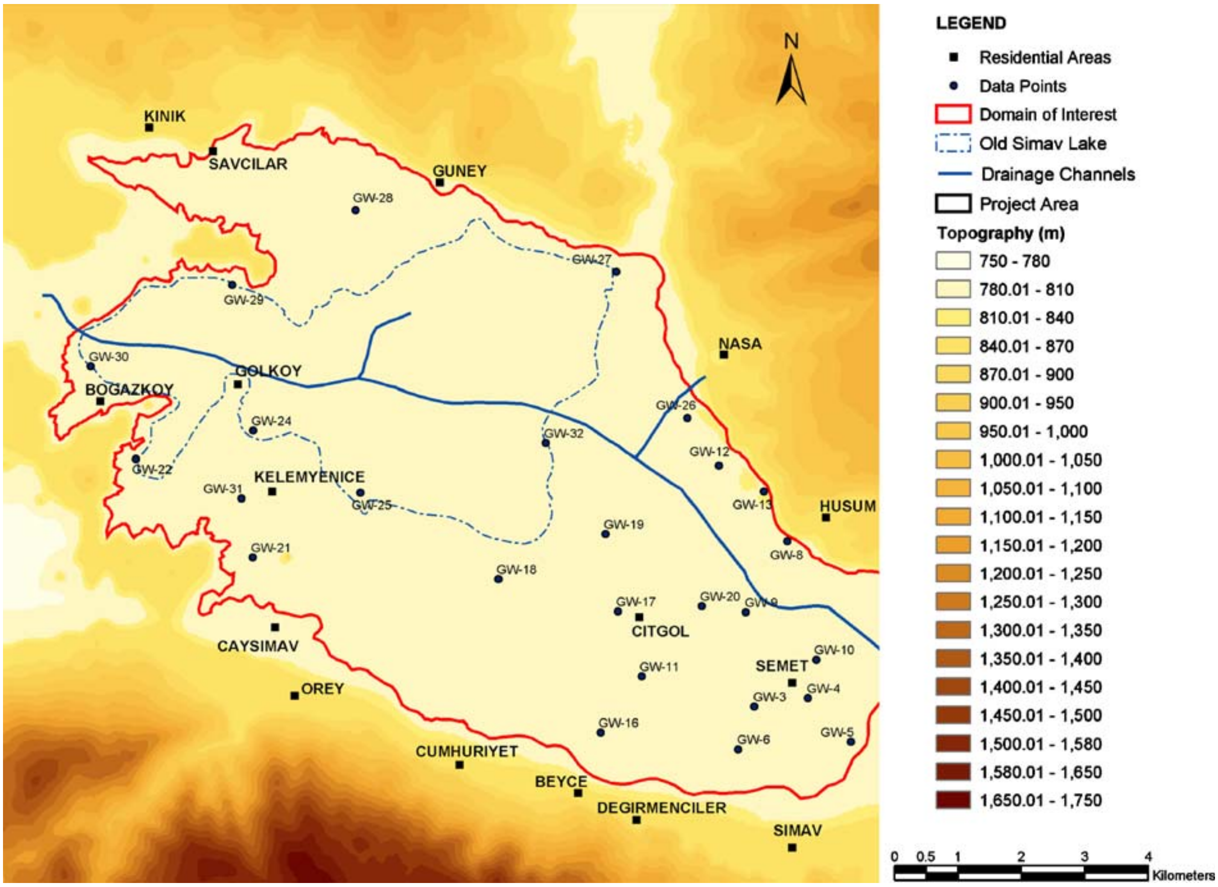

Figure 2 Sampling locations in Simav Plain.

formulated as a weighted average of all the ions available for analysis:

$$G_4 = \frac{w_4}{N}\sum_{k=1}^{N} r_k \tag{6}$$

where k is an incremental index, N is the total number of trace element available for the analysis, w is the weight value of this group and r is the rating value of each parameter as given in Table V. The fifth and the final category is the miscellaneous effects to sensitive crops that is represented by nitrate–nitrogen and bicarbonate ions and the pH of the water, and is formulated as a weighted average:

$$G_5 = \frac{w_5}{3}\sum_{m=1}^{3} r_m \tag{7}$$

where m is an incremental index, w is the weight value of this group and r is the rating value of each parameter as given in Table III.

After the total value of the index is computed, a suitability analysis is done based on the three different categories given in Table VI. The values given in the table is obtained by assigning different rating factors (i.e., 1, 2 and 3) to each parameter without changing its weighing coefficient, thus yielding three different index values (i.e., 45, 30 and 15). The medians of these values are used to set the upper and lower limits used in each category specified in Table VI.

The proposed technique is implemented via grid datasets and grid processing procedures of GIS. Although the technique is independent from the GIS platform used, this study is conducted with the ArcGIS software of Environmental Systems Research Institute Inc (ESRI, 1999). Before starting the analysis, the point-based water quality database is converted to grid datasets for each parameter given in Tables III, IV and V. During this conversion, the cell size of grid datasets depends on the resolution of the point data. In general, the typical sizes of the grid range between 10 and

Table VII The results of water quality analysis in Simav Plain–1. Primary parameters

SAMPLE	X –	Y –	T °C	pH –	EC μS/cm	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	NO3–N mg/l	SO4 mg/l	HCO3 mg/l	Cl mg/l	SAR –
GW-3	670,530	4,330,884	16.2	7.34	807.0	100.01	38.83	11.57	1.63	0.17	167.07	244.32	16.0	0.25
GW-4	671,379	4,331,015	15.1	7.25	853.0	120.87	49.54	9.49	2.95	0.30	133.07	361.92	22.0	0.18
GW-5	672,057	433,0326	16.0	7.13	956.0	147.11	57.24	9.93	3.23	0.19	181.45	402.00	23.0	0.18
GW-6	670,280	4,330,208	15.0	7.22	902.0	130.47	49.38	25.44	2.22	1.59	155.14	418.80	55.0	0.48
GW-8	671,058	4,333,501	16.5	7.51	504.0	61.56	17.03	15.49	0.05	0.59	139.92	85.44	26.0	0.45
GW-9	670,401	4,332,374	17.6	7.10	707.0	98.00	26.48	46.48	4.20	0.67	154.21	312.24	21.0	1.08
GW-10	671,514	4,331,625	20.0	7.20	653.0	87.32	30.09	12.30	1.53	0.30	93.60	256.08	14.0	0.29
GW-11	668,755	4,331,362	23.5	7.32	665.0	96.46	25.87	25.87	1.66	0.30	60.49	512.40	23.0	0.60
GW-12	669,979	4,334,693	16.4	6.71	1,789.0	185.28	28.98	246.77	30.97	0.57	385.70	512.60	63.0	4.45
GW-13	670,685	4,334,288	17.0	7.43	337.0	48.17	12.27	15.68	3.05	6.40	382.40	115.20	16.0	0.52
GW-16	668,110	4,330,472	18.0	6.89	567.0	58.89	16.08	40.89	2.75	0.76	138.00	182.00	15.0	1.22
GW-17	668,381	4,332,390	25.7	6.90	569.0	89.56	26.75	15.17	1.66	0.30	101.60	306.24	15.0	0.36
GW-18	666,500	4,332,900	20.0	7.05	623.0	69.78	24.78	52.77	1.78	0.35	89.50	397.92	10.0	1.38
GW-19	668,189	4,333,616	19.0	6.41	1,600.0	79.29	17.69	296.96	24.39	4.60	474.80	612.00	65.0	7.85
GW-20	669,709	4,332,473	20.0	7.23	524.0	80.98	24.90	17.40	1.67	0.00	129.90	296.64	15.0	0.43
GW-21	662,623	4,333,242	15.4	7.25	342.0	46.98	14.91	7.24	1.64	6.60	34.80	216.72	10.0	0.24
GW-22	660,780	4,334,795	21.1	7.31	482.0	39.91	7.39	64.81	3.26	1.00	42.20	302.40	12.0	2.47
GW-24	662,632	4,335,241	15.6	7.40	297.0	42.94	12.47	9.06	2.40	2.40	36.20	196.80	9.0	0.31
GW-25	664,319	4,334,263	17.0	7.26	535.0	64.11	18.43	44.88	1.72	0.20	105.70	314.88	11.0	1.27
GW-26	669,479	4,335,443	15.5	7.36	705.0	121.91	19.47	8.83	1.38	12.60	32.70	410.40	15.0	0.20
GW-27	668,358	4,337,751	17.5	7.24	750.0	117.82	27.86	24.82	9.47	6.40	75.30	410.40	10.0	0.53
GW-28	664,246	4,338,726	14.7	7.25	583.0	100.19	14.32	15.65	4.42	1.60	49.20	312.00	12.0	0.39
GW-29	662,301	4,337,548	19.5	7.60	401.0	46.19	15.09	15.78	0.37	17.80	63.80	165.60	8.0	0.52
GW-30	660,066	4,336,255	15.4	6.95	1,503.0	286.11	38.48	28.00	16.97	6.90	182.40	693.60	65.0	0.41
GW-31	662,446	4,334,177	15.5	7.40	288.0	39.01	14.48	11.19	1.94	1.80	28.00	192.00	8.0	0.39
GW-32	667,243	4,335,043	19.5	7.19	700.0	88.79	23.49	49.87	2.35	5.10	37.80	460.80	8.0	1.22

1,000 m. The procedure, however, is flexible such that finer grids could also be used in the analysis provided that there is sufficient point-wise data to support this decision. It is also important to note that the datasets must be in projected coordinate systems for proper processing of the grids. During the conversion from point to grid datasets, an interpolation procedure is implemented. This interpolation phase is extremely important since the interpolated grid is only as good as its point input data. In this particular study, it is possible to use an inverse distance weighing interpolation method or krigging technique. Yet, a more important point than the interpolation technique is the extent of the domain (i.e., the domain of interest) where the point database could be gridded with highest possible accuracy. Within the domain of interest, the conversion from point to grid dataset is efficient and dependable and hence, the output grid highly represents the spatial distribution of the parameter in actual field conditions. Once the grid datasets are ready within the domain of interest, they are transformed to index values (i.e., 1, 2 and 3) based on the criteria specified in Tables III, IV and V. The transformation is performed by a computer program that uses the interpolated parameter grid as an input file. The output of the program is also an index grid, which contains index values from 1 to 3. Finally these index grids (i.e., one for each parameter of the index) are combined according to Equation (2) to obtain the IWQ index value. The final IWQ grid map is later evaluated based on the suitability criteria given in Table VI.

5 Case Study: Simav Plain

5.1 General characteristics

The Simav Plain is located within the boundaries of the district of Simav in Kutahya Province of Turkey. It is situated about 45 km southwest of the city of Kutahya in

Table VIII The results of water quality analysis in Simav Plain–2. Trace elements

SAMPLE	Al ppb	As ppb	B ppb	Be ppb	Cd ppb	Co ppb	Cr ppb	Cu ppb	Fe ppb	Li ppb	Mn ppb	Mo ppb	Ni ppb	Pb ppb	Se ppb	V ppb	Zn ppb
GW-3	11.0	133.0	51.0	0.05	0.05	0.23	2.0	0.7	616.0	2.6	1,835.74	2.8	0.2	0.1	0.5	0.2	30.5
GW-4	52.0	18.3	53.0	0.05	0.08	0.31	4.0	30.9	290.0	3.8	331.20	1.6	1.4	2.3	0.5	0.9	121.8
GW-5	18.0	56.9	57.0	0.05	0.05	0.67	5.1	2.2	1,152.0	4.3	1,984.94	2.3	2.3	2.8	0.5	0.2	165.4
GW-6	25.0	561.5	65.0	0.05	0.05	0.76	5.0	2.1	4,122.0	2.1	2,966.46	5.6	1.9	0.5	0.5	0.4	15.0
GW-8	12.0	5.3	45.0	0.05	0.05	0.10	2.3	8.4	161.0	2.5	1.85	0.8	0.4	0.6	0.5	3.0	26.2
GW-9	276.0	384.2	253.0	0.05	0.07	0.41	4.0	6.5	259.0	67.2	1,808.86	4.7	1.1	1.2	0.5	0.3	3,451.8
GW-10	3.0	8.9	35.0	0.05	0.05	0.12	1.4	1.0	10.0	4.1	134.38	3.1	0.2	0.1	0.5	1.3	1.0
GW-11	1.0	22.2	33.0	0.05	0.05	0.13	3.6	0.7	107.0	3.4	589.29	3.9	0.2	0.1	0.5	0.5	1.5
GW-12	8.0	143.0	1,772.0	0.13	0.05	2.25	21.9	4.4	85.0	807.1	3,356.41	4.0	3.9	0.3	0.7	2.5	13.1
GW-13	365.0	10.4	70.0	0.12	0.05	0.95	2.0	3.1	471.0	42.9	57.86	0.4	2.1	0.9	1.0	17.6	30.5
GW-16	71.0	312.3	26.0	0.05	0.05	0.37	5.9	1.0	14,551.0	7.8	1,715.24	0.2	1.2	1.6	0.5	0.4	69.5
GW-17	18.0	7.1	32.0	0.05	0.05	0.22	2.4	0.9	10.0	4.2	65.50	2.7	0.2	0.9	0.5	1.0	8.9
GW-18	2.0	144.8	29.0	0.05	0.11	0.31	3.7	0.6	10.0	3.5	2,275.93	10.4	0.3	0.1	0.5	0.9	0.8
GW-19	469.0	21.1	2,538.0	0.16	0.06	0.76	14.6	2.6	9,542.0	869.2	517.75	0.3	3.5	2.9	0.8	2.2	42.0
GW-20	19.0	27.0	36.0	0.05	0.05	0.09	1.9	35.5	151.0	10.7	107.07	3.2	0.2	1.5	0.5	0.9	42.1
GW-21	23.0	0.9	20.0	0.05	0.05	0.02	0.9	3.1	10.0	3.5	0.53	0.3	0.2	0.8	0.5	0.2	5.7
GW-22	64.0	177.2	48.0	0.05	0.05	0.16	1.2	1.3	714.0	127.4	110.88	1.1	0.2	0.7	0.5	5.6	2.1
GW-24	303.0	89.3	20.0	0.05	0.05	0.68	1.6	1.0	5,317.0	1.4	526.82	0.1	0.6	1.4	0.5	1.2	10.3
GW-25	6.0	20.7	30.0	0.05	0.05	0.04	1.8	0.5	3,876.0	1.2	397.08	0.5	0.2	0.2	0.5	0.2	0.9
GW-26	241.0	7.3	20.0	0.05	0.05	0.24	15.1	3.8	257.0	0.6	13.73	0.2	0.2	1.0	0.5	9.2	5.9
GW-27	21.0	17.7	73.0	0.05	0.05	0.07	14.1	1.3	29.0	15.1	3.19	2.4	0.2	0.3	0.6	14.0	2.0
GW-28	69.0	19.0	20.0	0.11	0.06	0.89	1.3	1.4	407.0	1.6	2,059.20	1.4	0.3	0.5	0.5	5.7	6.1
GW-29	21.0	9.8	20.0	0.05	0.05	0.05	2.7	0.8	36.0	4.6	2.04	0.4	0.4	0.1	0.8	3.9	0.9
GW-30	239.0	213.2	131.0	0.05	0.05	0.26	2.9	2.9	553.0	79.5	2,492.64	2.3	0.5	2.2	1.0	0.5	17.5
GW-31	94.0	48.1	20.0	0.05	0.05	0.31	1.1	1.5	1,167.0	6.5	219.63	0.6	0.2	1.3	0.5	0.3	19.7
GW-32	3.0	216.5	30.0	0.05	0.05	0.04	1.7	0.7	3,752.0	6.1	1,843.40	0.3	0.2	0.1	0.5	0.2	0.8

western Anatolia (Figure 1). Within the plain, Simav, Citgol, Nasa, Kelemyenice, Caysimav, Degirmenciler, Beyce, Orey, Golkoy, Bogazkoy and Guney are the main population centers with a total population of about 55,000 according to 2000 census results. Agriculture is the main economic activity and the majority of the population is involved with small to medium scale agricultural production. In general terms, the region is not industrialized and there exits only a few agro-related industrial facilities in and around the plain. On the other hand, the hot water springs situated within the plain and the associated thermal tourism is a another source of income for the region's economy.

5.2 Hydrography

The Simav Plain is formed at the base of a graben area. The plain is surrounded by Ak Mountain to the north, Egrigoz Mountain to the east and Simav Mountains to the south. The City of Simav is located to the southeast of the plain (Figure 1). The majority of what is now known as the Simav Plain was once covered by the shallow Simav Lake that was drained in 1960s by the State Hydraulic Works (DSI) and was converted to agricultural land. Today, the Simav Plain Basin is mainly composed of an old dried lake bed that is regulated by a diversion weir constructed by DSI. The main drainage network that was used to drain the lake is still operative today and carries not only the return flows of agricultural irrigation but also the untreated sewage of Simav and other residential areas located within the plain.

The plain is situated in the Aegean Region but does not demonstrate typical characteristics of the mild and warm Aegean climate as it is located about 300 km inland and has an average elevation of about 950 m above mean sea level. In accordance with these characteristics, Simav Plain and its vicinity is considered to be in the Central Aegean climate zone, which shows the attributes of a transition zone from Aegean climate to Central Anatolian climate. Based on data from 1991–2000, the mean annual temperature of the region is 11.7°C. The hottest months of the year are July and August with monthly averages of 21.9 and 21.5°C, respectively. The coldest months, on the other hand, are January and February with monthly averages of 2.1 and 2.7°C, respectively. According to the

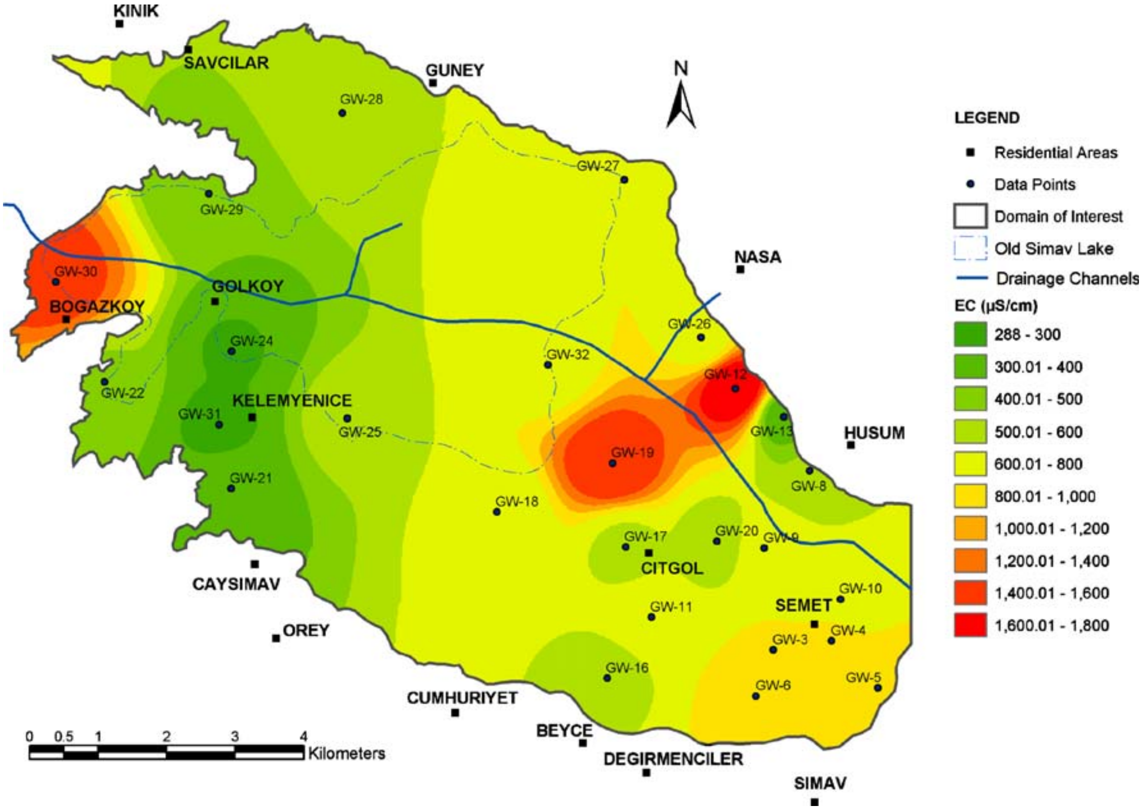

Figure 3 Electrical conductivity distribution in Simav Plain.

10 years of meteorological data, the region receives an average precipitation of 723 mm. The monthly averages of the highest and lowest precipitation occur in December and August with totals of 117.4 and 11.2 mm, respectively (DMI, 2005).

Due to its unique characteristics, the Simav Plain consists of a major unconfined alluvial aquifer with extremely permeable gravel and sand texture that is formed as a result of the long term deposits of Simav Lake and the tributaries draining to it. The groundwater table in the plain is close to the surface and it is possible to find numerous springs in the vicinity. Some of these springs are productive and could yield as high as 2.5 l/s. The dominant groundwater flow direction follows the flow path of Simav Creek and the drainage channel, and is directed towards north-northwest. The groundwater levels rise significantly in winter months and several wetlands form around the old Simav Lake. Due to its high water supply capacity, almost all irrigation water requirement of the plain is provided from groundwater and there are many wells developed in the surfacial aquifer. The depths of these wells range from 10 m in and around the old lake bed to 150 m in the outer parts of the plain.

5.3 Hydrogeology

The hydrogeology of the study area is governed by two major aquifer systems. The first one of these aquifer systems is the alluvial surfacial aquifer that supplies cold water. This system provides the majority of the groundwater extracted for drinking, irrigation and industrial use in the plain. The second aquifer, on the other hand, is a part of the local geothermal system formed along a major fault line that passes underneath the graben area. In this system, hot geothermal waters surface out from the fault line and mix with surface and subsurface waters of the plain. This system resulted in three major geothermal fields located at Nasa, Eynal and Citgol. Currently, these fields are used as thermal spas and further supply hot water for the central heating system of the city of Simav.

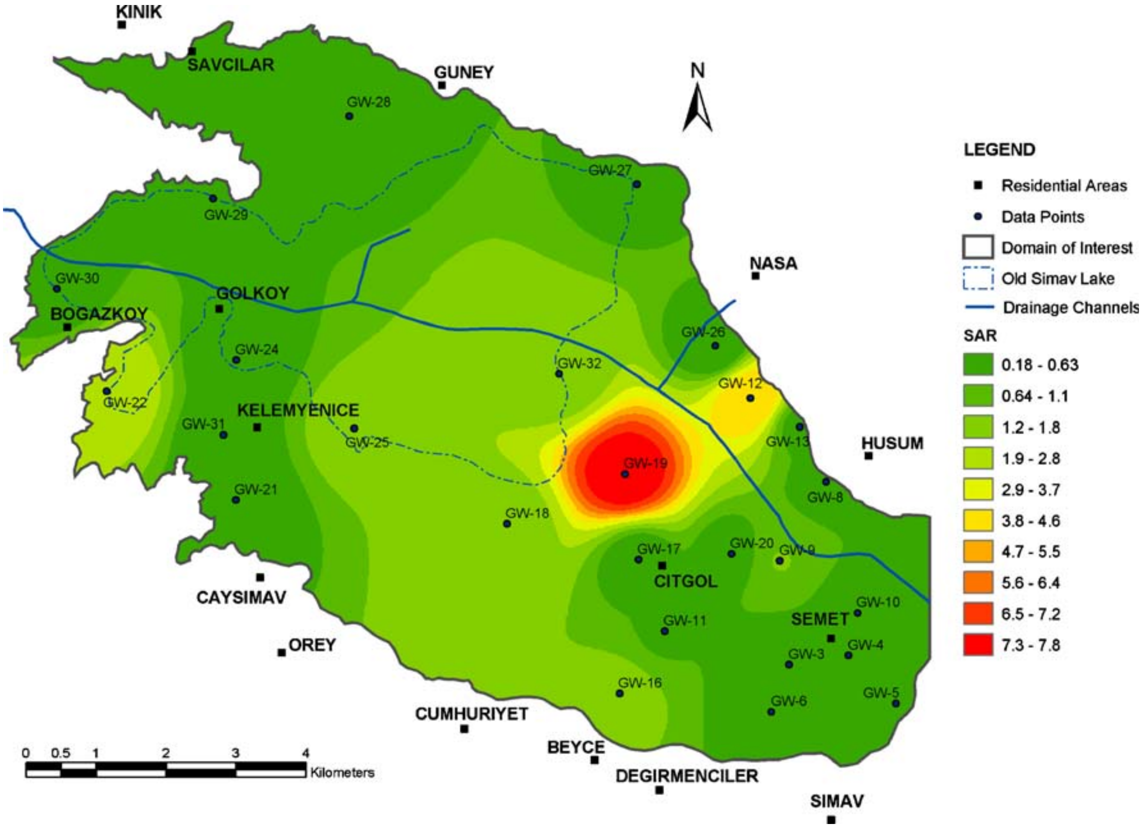

Figure 4 SAR distribution in Simav Plain.

The alluvial surfacial aquifer is mainly composed of sedimentary sands and gravels. The aquifer sometimes reaches 90 m in thickness and provides the biggest portion of the extracted groundwater. The sediments of the old Lake Simav demonstrate the characteristics of this alluvial layer. These sediments have originated from different lithology rocks found in the vicinity of the area. Rocks such as halides, gypsums and aragonites, which increase the salinity of the waters passing through them, are frequently found in the area and influence the quality of the groundwater.

The reservoir rocks of the geothermal field found underneath Simav Plain are composed of conglomerates, sandstones, limestones, schists and marbles that belong to Kizilbuk formation and Menderes Metamorphics. These rocks have been broken with the movement of the Simav graben fault and have been transformed into a fractured structure that plays an important role in the formation and storage of hot waters. In addition, it is also believed that a secondary reservoir system has developed in the young volcanic system located underneath Simav Plain as a result of basalt intrusion and lava flow. The bore log data obtained from a geothermal well indicates that the thickness of these Neogene-aged and volcanic reservoir rocks reach a total of about 400 m (Gemici & Tarcan, 2002).

The project area is located within in a tectonically active region where cold and hot subsurface water resources mix with each other. Particularly, the hot geothermal waters pollute the cold waters of the surfacial aquifer thermally and geochemically. Extensive pumping from the aquifer not only results in the declines of the regional groundwater levels in the surfacial aquifer but also force the hot waters rise up and blend with the cold waters.

Within the project area, most waste discharges from geothermal fields, industrial facilities and domestic sewage outflows are made to surface water drainage network, including the creeks and the drainage channels. As noted before, the governing groundwater flow direction in the surfacial aquifer

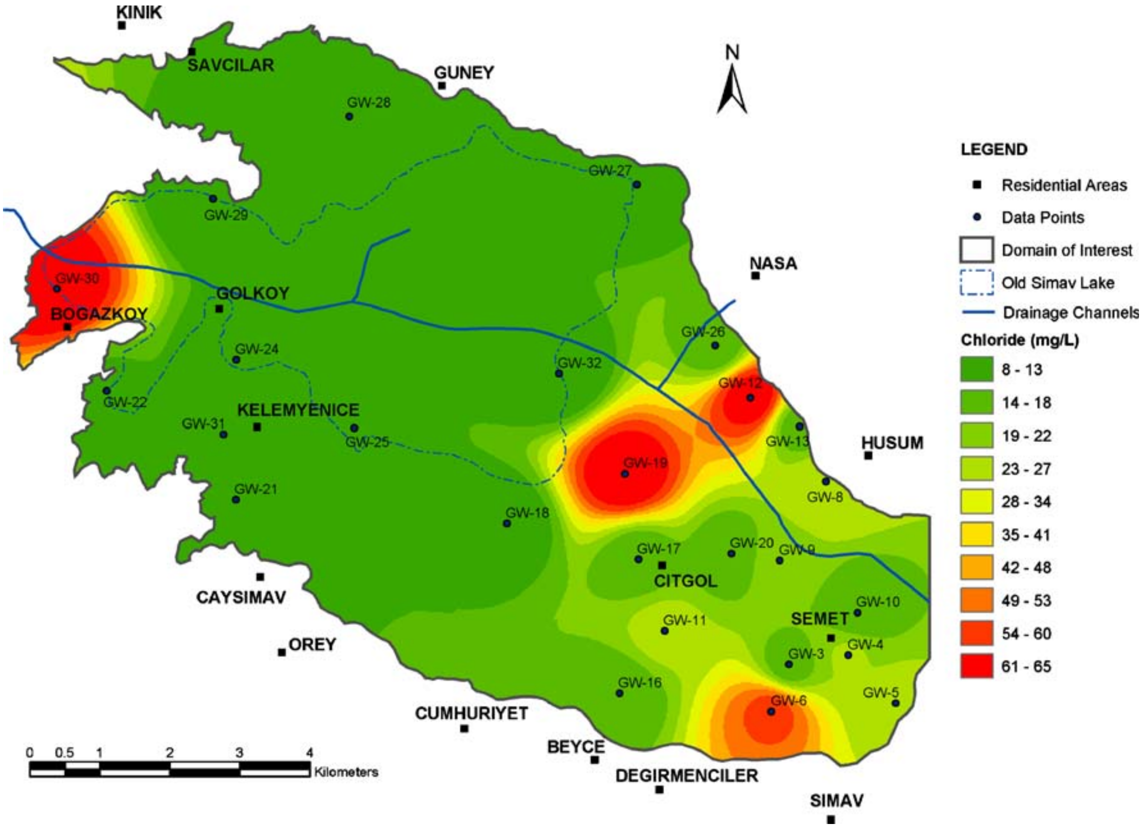

Figure 5 Chloride distribution in Simav Plain.

follows that of the surface flow pattern, which is from southeast to northwest. This parallelism between the surface and subsurface flow directions gives ample opportunity for contaminants in surface waters to influence the quality of subsurface waters due to the strong interactions between the two domains. The alluvium based formation of the surfacial aquifer increases the extent of these interactions due to its high hydraulic conductivity. Hence, it could be mentioned that the quality of groundwater in Simav Plain is strongly influenced from the quality of the surface waters, the interactions with geothermal waters as well as the lithology of the surfacial aquifer.

5.4 Agriculture and irrigation

As mentioned in previous sections, the economy of the Simav and its vicinity is based on agricultural production. With a total of 61 ha agricultural area, the Simav Plain is the center of this activity. Sunflower, bean, onion, potato and tomato are the main crops cultivated in the plain. Currently, individual wells drilled in the surfacial aquifer are used to irrigate these crops. The farmers generally do not prefer to use surface water resources as almost all creeks in the region are intermittent streams that dry up in summer months when the demand for irrigation waters are at its peak. Moreover, the few permanent creeks are too polluted to be used in irrigation as they continuously receive raw sewage discharges from nearby residential areas as well as waste geothermal fluid from the three hot springs. In this regard, groundwater is considered to be the only alternative for supplying irrigation water to the plain's fields.

5.5 Data preparation

The database used in this study is created by utilizing the data obtained from a total of 26 irrigation wells shown in Figure 2. These wells are selected randomly to obtain a homogeneous distribution within the plain. The details pertaining to the database is presented in

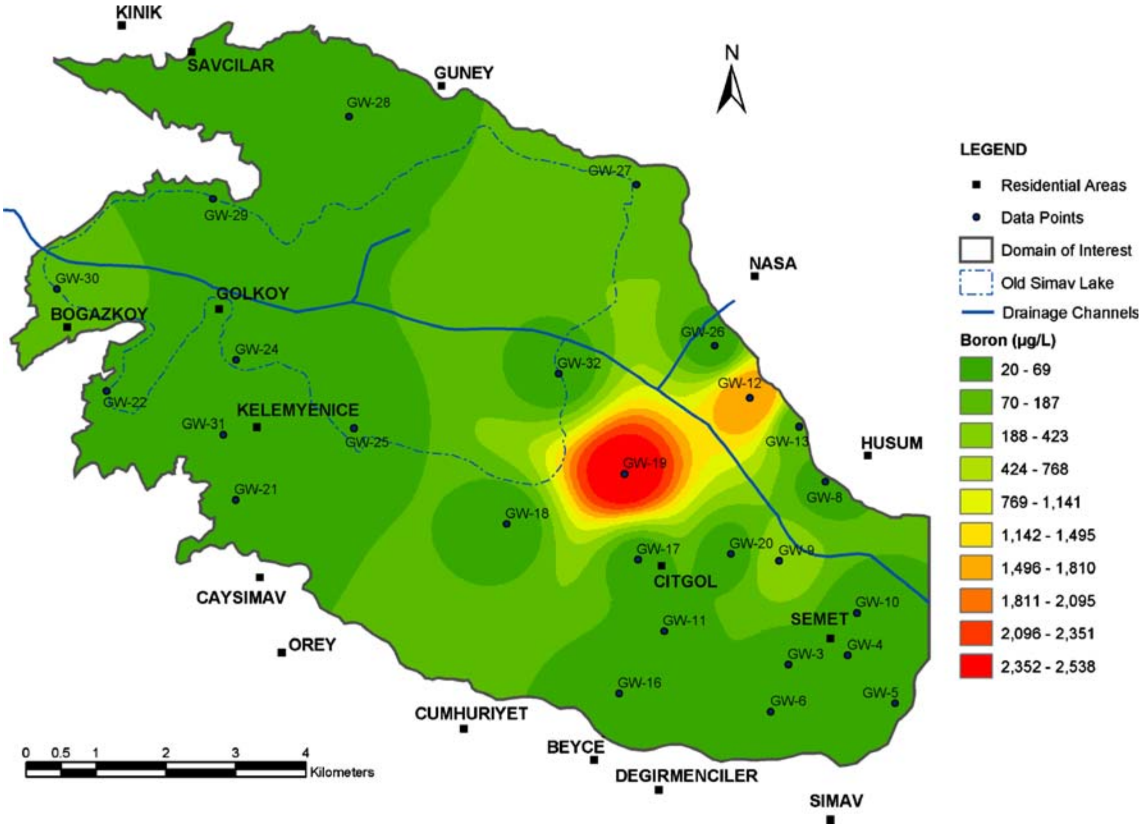

Figure 6 Boron distribution in Simav Plain.

Tables VII and VIII. From each well, two sets of samples are collected (i.e., 1,000 ml for anion analysis and 50 ml for cation analysis). The water samples are then stored in polyethylene bottles until analyzed for the physicochemical parameters given in Tables VII and VIII. It is important to note that nitric acid is added to the samples that are to be used for cation analysis to obtain a pH value of less than 2. The pH (WWT-pH330) and electrical conductivity (EC) (WWT-EC330) measurements are made on the field. Cations are analyzed with ICP-MS in Canadian ACME laboratories; chloride and bicarbonate ions are analyzed with volumetric methods; nitrate is measured by photometric methods and sulfate is analyzed with gravimetric methods in Dokuz Eylul University laboratories. SAR values are then computed using the Aquachem 3.70 computer program.

The GIS integration of the database is performed by ArcGIS computer program. During GIS analysis, the general project area is revised and reduced based on the locations of the wells and the boundaries of the plain. As a consequence of this revision, a domain of interest is drawn following the 800 m contour line that roughly corresponds to the boundaries of the Simav Plain as shown in Figure 2.

6 Results and Discussions

Once the water quality database given in Tables VII and VIII is transferred into GIS platform, grid datasets are created for each parameter within the domain of interest using inverse distance interpolation technique. First, the spatial distributions of these quality parameters are assessed with particular reference to the individual hazard groups discussed in previous sections. The parameter grids are then transformed into index grids using a computer program developed for this study. The individual parameter indices are then processed according to Equation (2) and five index maps are created for the corresponding hazard groups. Finally, these group maps are combined to form the final IWQ index map.

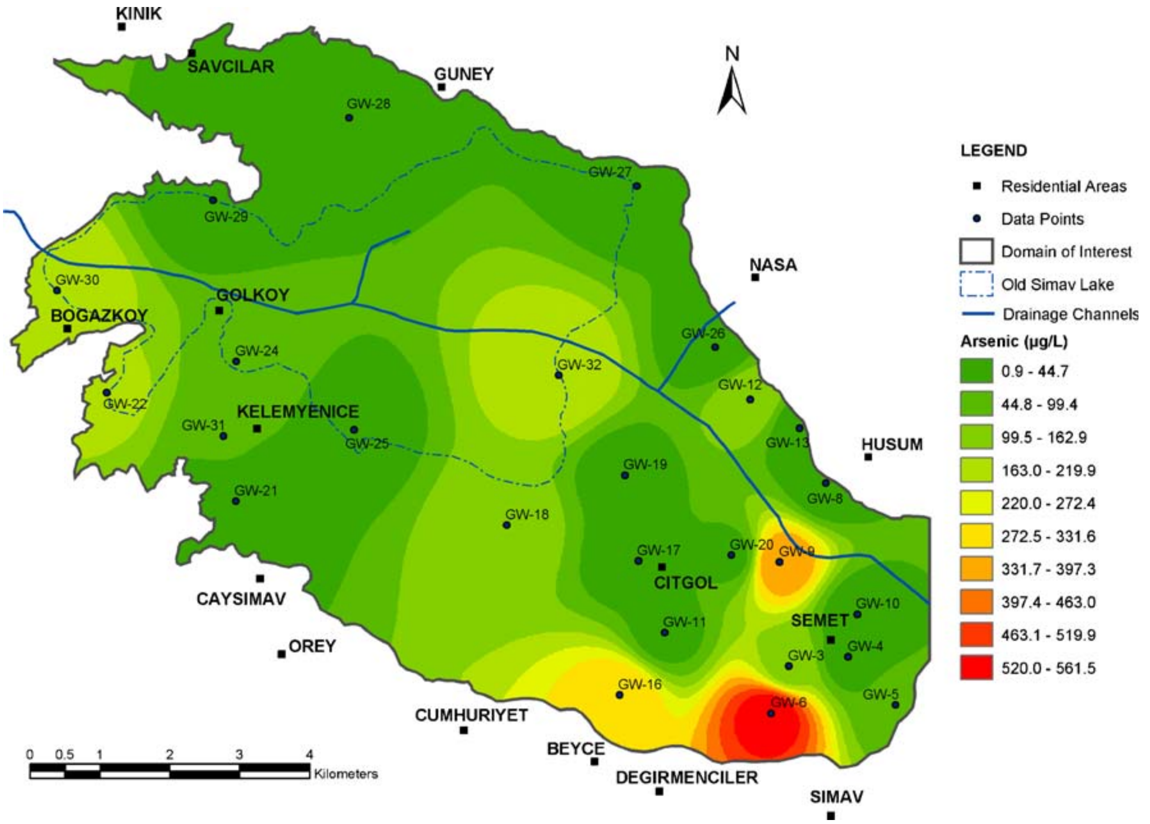

Figure 7 Arsenic distribution in Simav Plain.

6.1 Assessment of individual hazard groups

6.1.1 Salinity hazard

The spatial distribution of electrical conductivity measured in samples collected from 26 wells is presented in Figure 3. It can be seen from the figure that EC values are observed to cover a wide range from 288 μS/cm measured at GW-31 to 1,789 μS/cm measured at GW-12. As EC demonstrates the salinity hazard, one can conclude that the agricultural fields around Golkoy and Kelemyenice have the best quality irrigation water when salinity risks are considered. The high EC spots observed around Bogazkoy and the northern portions of Citgol are believed to be related to the geothermal water intrusion to the cold surfacial aquifer. Particularly, the geothermal fields located in Nasa and Citgol is responsible for the increased EC levels around Citgol. The high EC value around Bogazkoy might be attributed to surface pollutants found in the drainage channel due to its close proximity to GW-30.

6.1.2 Infiltration hazard

The spatial distribution of SAR is presented in Figure 4. It can be seen from the figure that the high SAR values are mainly observed around Citgol. As in the case of EC, this situation is also attributed to the hot geothermal water intrusion to the surfacial aquifer. The results of a previous study also verify this finding and reports that sodium is one of the main elements in the waters of the geothermal fields in Simav Plain (Gemici & Tarcan, 2002). When EC and SAR are combined to assess the infiltration hazard, it has been found out that these areas where groundwater is affected from the intrusion of geothermal fluid demonstrate moderately suitable areas for irrigation water extraction as high SAR and EC values counter balance the negative effects of each other.

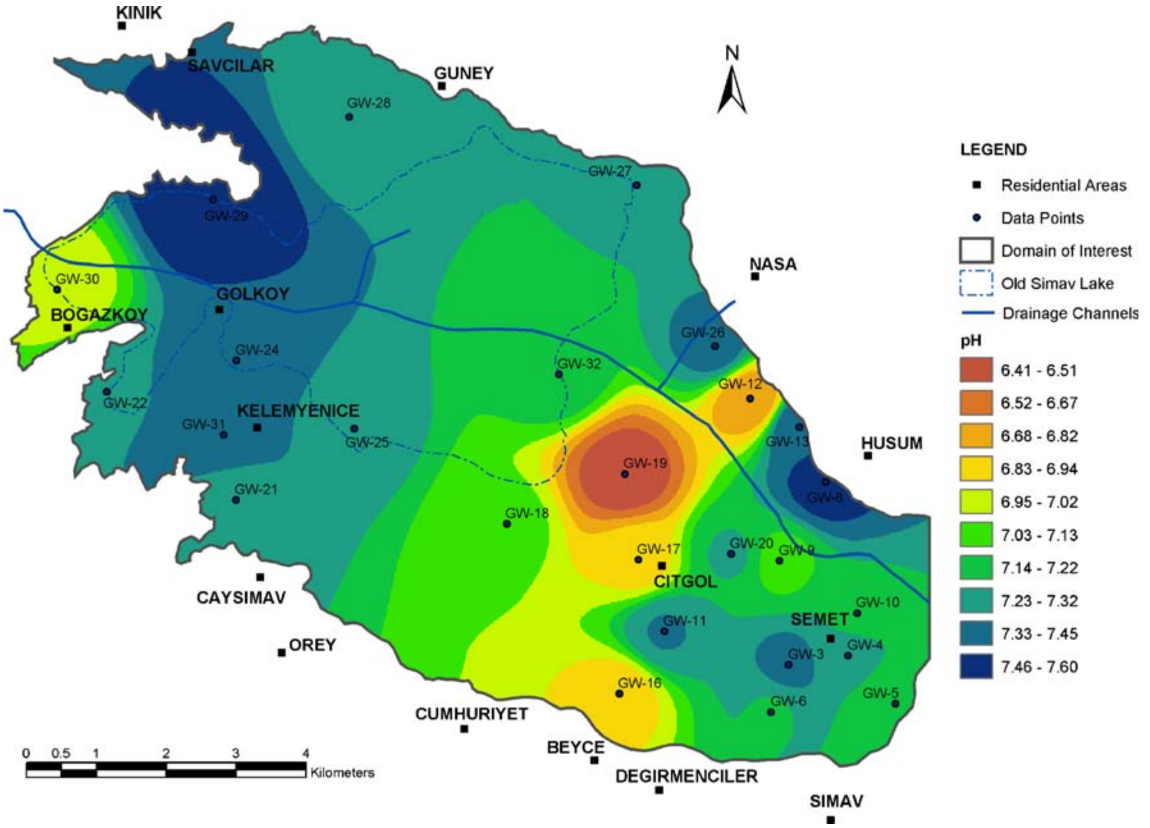

Figure 8 pH distribution in Simav Plain.

6.1.3 Specific ion toxicity

In addition to SAR distribution that is given in Figure 4, the chloride and boron maps of the domain of interest are presented in Figures 5 and 6, respectively, as the other parameters defining the specific ion toxicity. As seen from Figure 5, the chloride concentrations vary between 8 mg/l (i.e., measured at points GW-29, GW-31 and GW-32) and 65 mg/l (i.e., measured at points GW-19 and GW-30). Although chloride concentrations are found to be relatively higher in the vicinity of Citgol, Bogazkoy and Simav, they are below the lower limit of 140 mg/l representing good quality irrigation waters (Table I).

Similarly, the boron concentrations are observed to be highest at GW-12 and GW-19 with concentration values of 1,772 and 2,538 μg/l, respectively, as seen from Figure 6 and Table VII. As it is known that boron is an element that is rarely found in cold waters but is commonly observed at high concentrations in hot waters, high boron values are mainly attributed to the intrusion of hot geothermal fluid from Citgol and Nasa geothermal fields. Furthermore, boron has a high correlation with sodium ion in hot geothermal waters. As a natural consequence of this correlation, the SAR and boron distributions in the project area show fundamental similarities as seen from Figures 4 and 6.

6.1.4 Trace element toxicity

In this study, a trace element toxicity analysis is performed by using the results of 16 elements given in Table VIII. Only fluoride is excluded from the analysis as this parameter was not measured in Simav Plain study. It is important to note, however, that excluding fluoride did not create any error in the analysis as the overall toxicity analysis is normalized by the total number of elements included in the study. From the 16 elements included in Simav case study, the spatial distribution of arsenic is presented in Figure 7 as an example due to its extreme toxicity to plant and animal life. The results represent the fact that arsenic is found

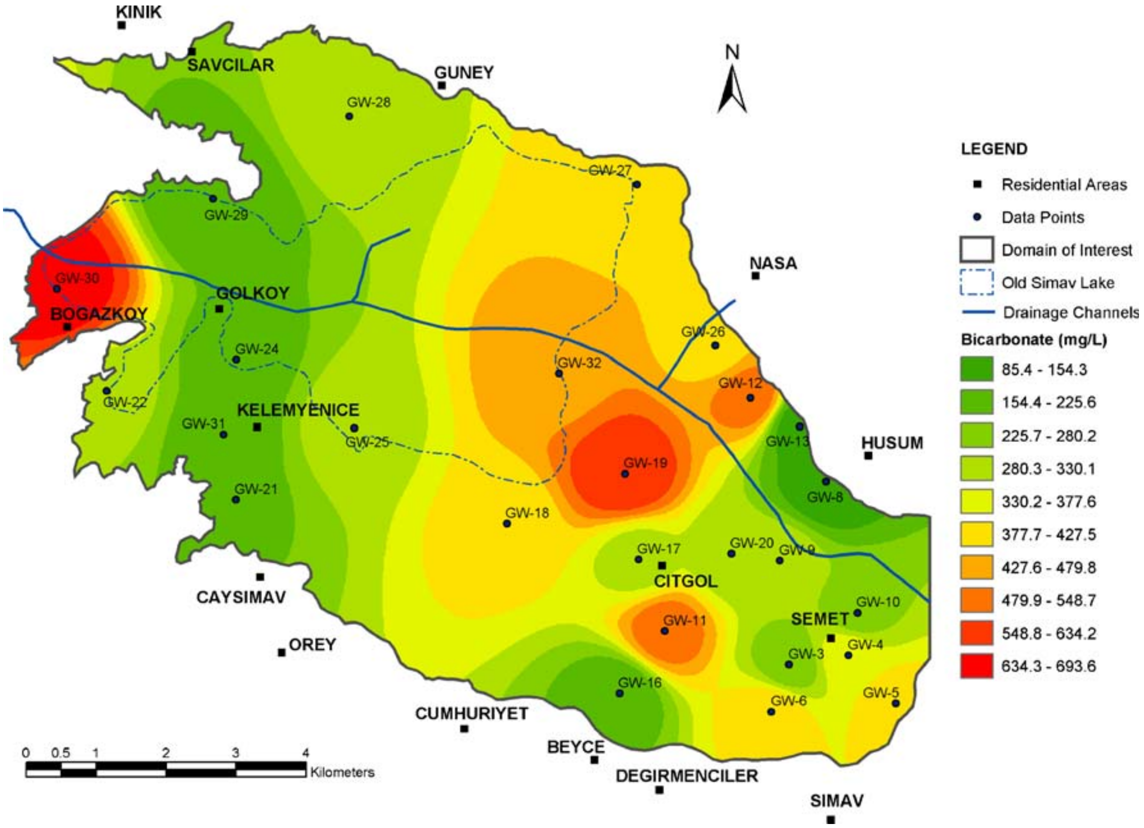

Figure 9 Bicarbonate distribution in Simav Plain.

in elevated concentrations in various sampling points. Accordingly, the quality of the irrigation waters is affected from these high concentrations of arsenic in the southern, central and western parts of the plain. Other elements demonstrate different patterns but are not presented herein due to space limitations.

When the irrigation water quality in Simav Plain is analyzed with respect to the 16 trace elements, it has been found out that the groundwater quality in the plain falls in moderate quality class. The high concentrations of some of these elements could be explained by the influence of geothermal waters originated as the result of active tectonics and volcanism underneath the plain. Relatively high concentrations of arsenic, lithium, selenium and zinc might also originate from the geological formations in around the plain and are also attributed to contamination of cold waters via hot geothermal fluid. Although not used very commonly in assessing the quality of irrigation waters, these elements have turned out to be a major tracer for discovering the overall quality of groundwater in the plain.

6.1.5 Miscellaneous effects

The spatial distributions of pH, nitrate–nitrogen and bicarbonate ion in the plain are presented in Figures 8, 9 and 10. As seen from these figures, the pH and bicarbonate distributions demonstrate a negative correlation. The pH of the water around Citgol is acidic in nature due to the influence from geothermal waters. It has been observed that the bicarbonate ion concentrations are high in these parts of the plain and in the vicinity of Bogazkoy. Particularly, the bicarbonate concentrations exceed the allowable limit of 500 mg/l at GW-19 and GW-30. In other areas, the groundwater's pH is neutral or slightly basic and the bicarbonate concentrations are relatively lower. When nitrate concentrations are analyzed, it could be seen that maximum values are observed at GW-26 and GW-29. Both points are close to residential areas and these relatively high values might be attributed to local uncontrolled sewage discharges as there is no engineered sewerage system within the plain. With respect to all three parameters that comprise the

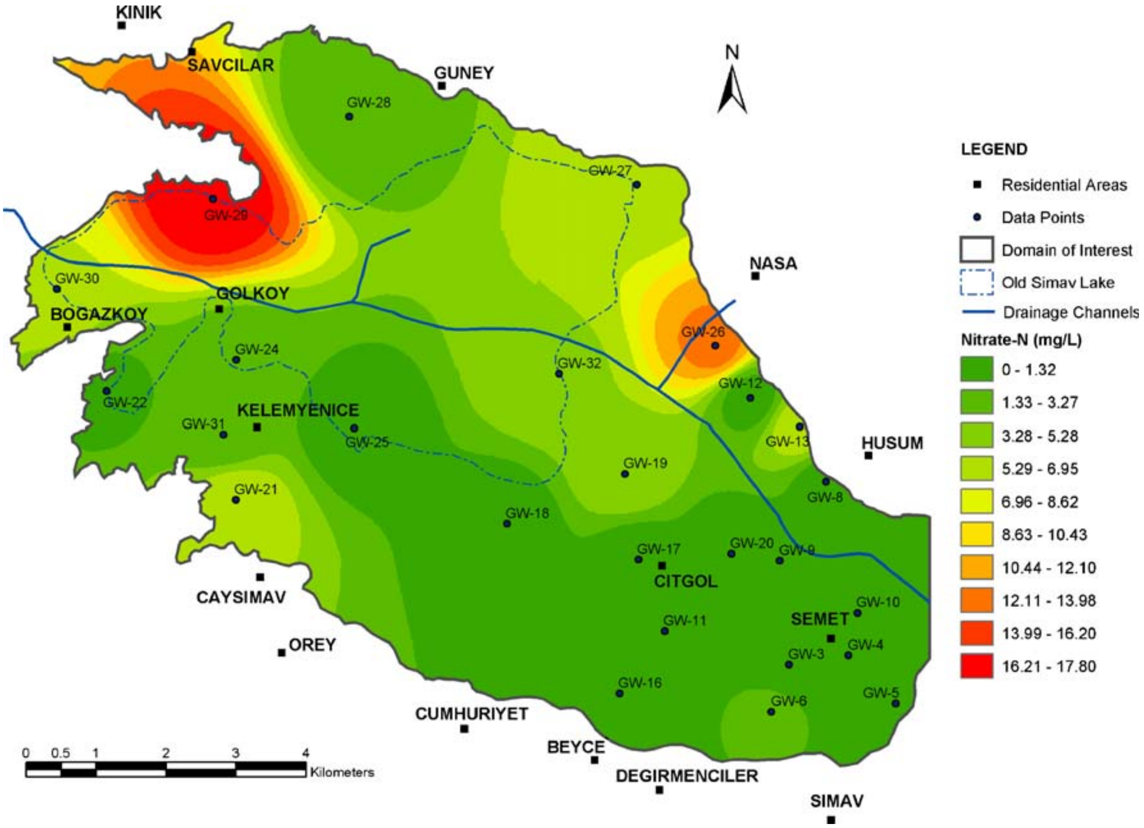

Figure 10 Nitrate–nitrogen distribution in Simav Plain.

miscellaneous effect, the irrigation water quality in the plain is poor around Citgol and Bogazkoy (i.e., sampling points GW-19 and GW-30) due to elevated concentrations of bicarbonate. In other parts of the domain of interest, the plain's groundwater resources are moderate based on these three parameters.

6.2 Discussion of irrigation water quality index

The linear combination of these index grids according to Equation (2) gives the IWQ index map shown in Figure 11. This figure represents the spatial distribution of the IWQ index within the domain of interest and could be considered as a general suitability map for providing irrigation water from surfacial aquifer. Since the map shows the spatial distribution of groundwater quality in the plain as index values, it is now much easier for a decision maker to assess the quality of groundwater for irrigation purposes and further locate the most suitable site for drilling wells to extract irrigation waters.

The suitability map obtained from the computed index value is evaluated according to three categories given in Table VI. When the computed index value is bigger than 37, the corresponding area is considered to have minimum problems with respect to irrigation quality. Therefore, a well drilled in this zone is considered to represent ideal conditions for irrigation water quality. When the suitability map presented in Figure 11 is analyzed, it is seen that the most suitable localities for extracting irrigation waters lies to the mid sections of the plain. These areas are far away from the three geothermal fields located to the south and southeast parts of the plain.

When the computed index value is between 22 and 37, the corresponding waters demonstrates moderate suitability for irrigation purposes. Within this range, values higher than 30 are considered to represent waters that could be easily used on resistant crops. These waters generally obtain high scores from the most important parameters including salinity hazard and infiltration and permeability hazards. On the other hand, values below 30 indicate waters that should only be used with caution and better be avoided, particularly for sensitive crops, if a better alternative

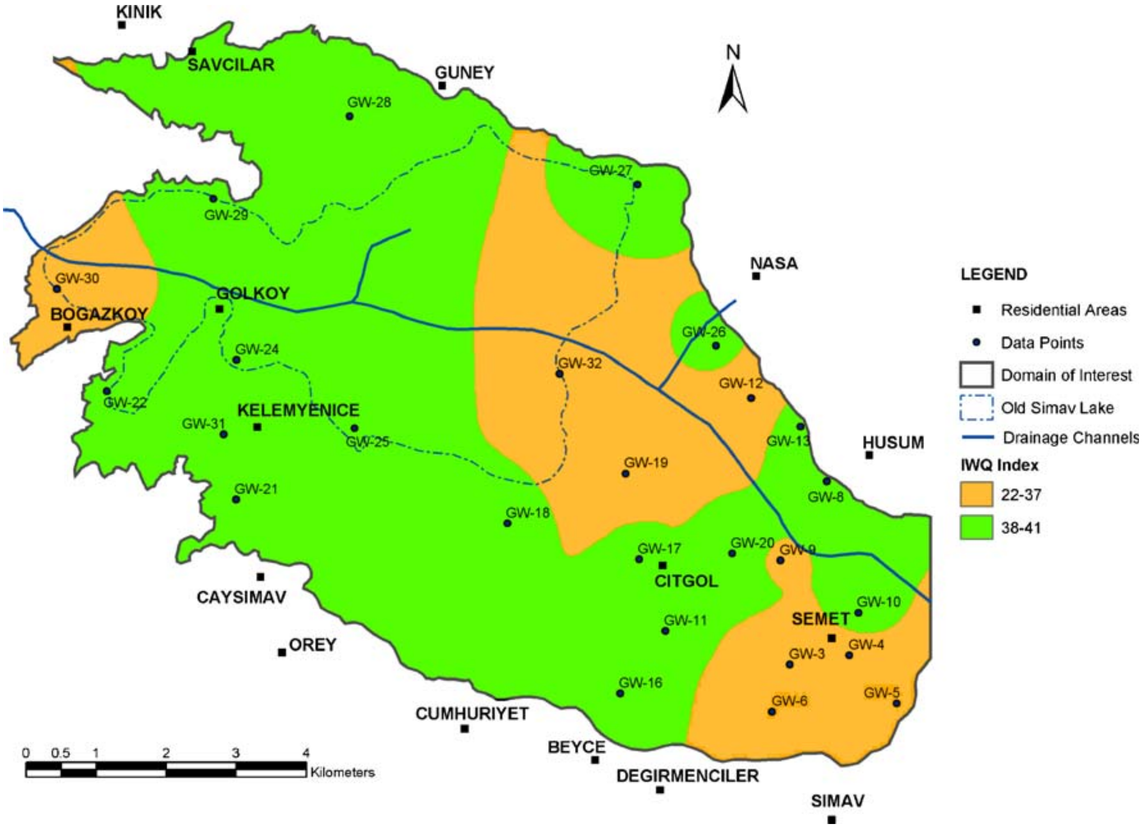

Figure 11 IWQ index map of Simav Plain.

is present. These areas generally have low scores from the most important parameters including salinity and infiltration hazards. Under extreme conditions, water extracted from these locations could be used with caution. In the study area, these areas are mostly located in the central and eastern parts of the domain of interest. These areas correspond to the areas which are under the influence of geothermal waters as well as uncontrolled sewage discharges.

Finally, areas with IWQ index values of less than 22 are considered to be poor quality irrigation waters and are not suitable for irrigating agricultural fields. Such waters could impair soil quality and result in yield loss. As a rule of thumb, water extraction from such areas should be avoided. Within the scope of this study, there are no such areas within the domain of interest that must be avoided.

According to the overall index map, it could be mentioned that the groundwater quality in the surfacial aquifer in Simav Plain is currently suitable for use in irrigation. However, there are several factors that deteriorate this status including the intrusion of hot geothermal fluid to the surfacial aquifer and the uncontrolled sewage disposal from the residential areas in the plain. The final map is believed to be a suitable tool in future agricultural management plans and in determining the most suitable site for drilling irrigation wells and for assessing the overall groundwater quality.

7 Conclusion

In this study, a new GIS-integrated tool is introduced to assess the quality of irrigation waters with regards to the potential soil and crop problems. The proposed procedure is mainly an index method that considers the most significant problems (i.e., salinity, infiltration, toxicity) associated with poor quality irrigation waters. The technique linearly combines the associated quality parameters and forms the proposed IWQ index. The integration of GIS simplifies the entire analysis procedure and allows a spatially distributed assessment of the regional quality pattern.

The technique requires the analysis of both the major physicochemical quality parameters as well as some of the trace elements found in the irrigation water. In order to obtain satisfactory results, it is important to obtain a moderately uniform spatial distribution of the data points in the analysis domain. While this might not always be possible, it is deemed crucial for successful interpolation of the results within the domain of interest. Once the resulting suitability map is obtained, the proposed methodology is believed to provide a fairly simple analysis tool even for a non-technical decision maker and/or a farmer.

The developed technique is implemented to assess the irrigation water quality of the Simav Plain located in western Anatolia, Turkey. Based on the results of this application, it has been found out that the local groundwater quality in the surfacial aquifer is fairly good and the aquifer waters are mostly suitable for irrigation purposes. In addition, the study also provided vital information on the probable pollution mechanisms that might influence the aquifer. Accordingly, the geothermal fields within the plain could be considered as a potential thermal and geochemical polluter of the aquifer. Moreover, the uncontrolled sewage disposal is another important pollution mechanism of surfacial aquifer as the groundwater table is close to the surface and the hydraulic conductivity of the aquifer material is comparatively high.

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