Research article

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Revista
Facultad Nacional
de Agronomía

UNIVERSIDAD
NACIONAL
DE COLOMBIA

Assessment of the hazards associated with water quality for irrigation in the Environmental Interceptor Canal of the RUT District, Colombia

Evaluación de los peligros asociados a la calidad del agua para riego en el Canal Interceptor Ambiental del Distrito RUT, Colombia

https://doi.org/10.15446/rfnam.v79.120876

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ABSTRACT

Keywords:
Agricultural resources
Corrosion
Risk management
Soil salinity
Water allocation

The Environmental Interceptor Canal supplies irrigation water to approximately 2,951 ha of agricultural land, primarily using pumped river water and effluents from the municipalities of Roldanillo, La Unión, and Toro's domestic wastewater treatment systems. In response to declining crop productivity, increased operational costs of irrigation systems, and constraints on export activities, this study aimed to evaluate the potential hazards associated with the use of water from this source for agricultural irrigation. Three composite sampling campaigns were conducted at seven points along the canal, and physicochemical and microbiological parameters were analyzed following standardized methodologies. The results revealed four main issues: a high microbiological hazard, evidenced by median fecal coliform (FC) concentrations exceeding 10,000 MPN 100 mL^{-1}; a moderate to high hazard of chemical soil degradation due to the presence of salts and sodium (Na^{+}); a high corrosion hazard; and a high hazard of emitter clogging associated with iron (Fe^{2+}) concentrations above 1.5 mg L^{-1} and elevated median concentrations of total suspended solids (TSS). Overall, the results indicate that the water quality of the canal presents significant limitations for agricultural irrigation, highlighting the need to implement management, treatment, and control measures to reduce operational risks, comply with regulatory criteria, and improve the sustainability of irrigation systems and agricultural productivity in the study area.

CITATION: Castillo Sánchez L, Echeverri Sánchez AF, Carreño Sánchez MM, Barona Ramírez SM and Jaramillo Llorente MF (2026) Assessment of the hazards associated with water quality for irrigation in the Environmental Interceptor Canal of the RUT District, Colombia. Revista Facultad Nacional de Agronomía Medellín 79: e120876. doi: https://doi.org/10.15446/rfnam.v79.120876

RESUMEN

Palabras clave:
Recursos agrícolas
Corrosión
Gestión de riesgos
Salinidad del suelo
Asignación de agua

El Canal Interceptor Ambiental abastece agua de riego a aproximadamente 2.951 ha de uso agrícola, utilizando principalmente agua bombeada de un río y descargas provenientes de los sistemas de tratamiento de aguas residuales domésticas de los municipios de Roldanillo, La Unión y Toro. Ante el descenso de la productividad de los cultivos, el aumento de los costos operativos de los sistemas de riego y las restricciones para la exportación, este estudio tuvo el objetivo de evaluar los peligros potenciales asociados al uso del agua de esta fuente para riego agrícola. Se realizaron tres campañas de muestreo compuesto en siete puntos a lo largo del canal, analizando parámetros fisicoquímicos y microbiológicos conforme a las metodologías estandarizadas. Los resultados evidenciaron cuatro problemáticas principales: un elevado peligro microbiológico, evidenciado por medianas de coliformes fecales (FC) superiores a 10.000 NMP 100 mL^{-1}, medio a alto peligro de degradación química de suelos a causa de la presencia de sales y sodio (Na^{+}), alto peligro por corrosión y alto peligro de taponamiento de emisores de riego debido a la concentración de hierro (Fe^{2+}) mayores a 1,5 mg L^{-1} y concentraciones medianas elevadas para los sólidos suspendidos totales (SST). En conjunto, los resultados indican que la calidad del agua del canal presenta limitaciones relevantes para su uso en riego agrícola, lo que resalta la necesidad de implementar medidas de manejo, tratamiento y control que permitan reducir los riesgos operativos, cumplir con los criterios regulatorios y mejorar la sostenibilidad de los sistemas de riego y la productividad agrícola en la zona.

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Received: October 2, 2025; Accepted: January 29, 2026
Rev. Fac. Nac. Agron. Medellín 79: e120876. 2026.

ISSN 0304-2847 / e-ISSN 2248-7026

Water scarcity and contamination of water sources have become major global challenges, affecting not only ecosystems but also food security and the economic stability of many regions (Ingrao et al. 2023). Agriculture, which depends heavily on irrigation water (Pardo Picazo et al. 2018), is particularly vulnerable, as both the availability and quality of water directly impact irrigation infrastructure, soils, crops, and even human health—making it a critical factor for sustainable development (Fernandes et al. 2023). Faced with the high demand and limited availability of water in terms of both quality and quantity, many countries have turned to alternative water sources, such as treated wastewater or surface waters of compromised quality (Angelakis et al. 2024). However, the use of these sources requires rigorous evaluation to prevent environmental, agronomic, and health-related risks.

In Colombia, severe problems persist regarding water scarcity and quality. Although the country has a robust regulatory framework governing water resource management, administrative deficiencies and socioeconomic challenges hinder effective implementation (Cardona-Almeida and Suárez 2024). This situation has, to some extent, prevented the development of adequate wastewater management infrastructure and limited the capacity for monitoring, control, and enforcement regarding impacts on water sources across much of the national territory. In addition, the Colombian regulatory framework for irrigation water quality, as established under Decree 1076 of 2015 of the Ministerio de Medio Ambiente y Desarrollo Sostenible (2015), defines minimum threshold values for selected parameters but lacks a systematic classification and categorization based on their potential impacts on the agricultural sector.

In response to these institutional and operational limitations, recent literature has developed a range of approaches aimed at evaluating the risks associated with the quality of water used for irrigation. Among these, the work of Barona (2022) is particularly noteworthy, as proposed by the Comprehensive Irrigation Water Quality Index (IICAR), designed to assess the potential hazard posed by irrigation water quality within a risk management framework. This index integrates physicochemical and microbiological parameters linked to impacts on soils, crops, human health, and irrigation infrastructure. Its application in a Colombian hydrographic subzone revealed the presence of localized risks, even where conditions with minimal restrictions predominated, underscoring the need for differentiated monitoring and control strategies.

Nevertheless, water irrigation quality in artificial conveyance systems has received limited attention, as most existing approaches have been applied primarily to natural water sources. In the Colombian context, this gap is particularly relevant in irrigation districts, where pressures related to water availability converge with the exposure of productive systems to physicochemical and microbiological risks. Consequently, studies focused on the integrated identification of these risks in artificial canals within irrigation districts remain scarce, constraining the understanding of their effects on agricultural productivity and the long-term sustainability of irrigation systems.

The Roldanillo–La Unión–Toro Land Improvement District (RUT District), considered one of the most productive agricultural areas in the country, is fully immersed in this problem, because includes an Environmental Interceptor Canal extending 31 km, which is fed by both the Cauca River and effluents from the wastewater treatment systems of the aforementioned municipalities—systems that show deficiencies due to deteriorating infrastructure. In addition, the Cauca River exhibits degraded water quality because of contaminant accumulation from various upstream municipalities, including the urban area of Cali (Galvis et al. 2018). This situation compromises the safety of irrigation water used in the RUT District, particularly within the canal’s coverage area of approximately 2,951 ha of crops, reflected in rising irrigation system operational costs and export restrictions for agricultural products.

The quality of water used for agricultural irrigation directly influences the sustainability of production systems, as certain components can have adverse effects on different receiving elements. Elevated concentrations of soluble salts, toxic trace elements, or substances that promote scaling and corrosion processes can reduce agricultural productivity and affect human health (Fernandes et al. 2023; Helmecke et al. 2020). Criteria for assessing the impact of irrigation water quality are established in terms of microbiological parameters (FAO and WHO 2021) and physicochemical parameters such as dissolved solids (DS), cations and anions in water (Shah et al. 2018; Singh et al. 2018). These variables are often used in indices such as the Sodium Adsorption Ratio (SAR), Electrical Conductivity of water (ECw), pH and Langelier Saturation Index (LSI) among others (Shah et al. 2018). These indicators are particularly relevant given their demonstrated effects on soil health, human health, crops, and irrigation infrastructure (Tartabull and Betancourt 2016; Demerdash et al. 2022).

In response to these challenges, the aim of this study was to evaluate the potential hazards associated with using water from the Environmental Interceptor Canal for irrigation purposes. The research focused on identifying potential risks affecting irrigation infrastructure, agricultural soils, crops, and human health, considering both temporal variability (across three sampling campaigns) and the spatial distribution of identified hazards at various points throughout the system.

MATERIALS AND METHODS

Study area

The RUT District is in the southwestern region of Colombia, in the northern part of the Valle del Cauca Department, within the RUT watershed. The district spans the area between the foothills of the Western Andes and the left bank of the Cauca River, encompassing territories under the jurisdiction of the municipalities of Roldanillo, La Unión, and Toro (Figure 1). The region has a moderately warm climate with an average temperature of 24 °C and a bimodal rainfall distribution, with a mean annual precipitation of 1,015 mm and an average annual evaporation of 1,145 mm. The total area of the RUT District is approximately 10,243 hectares, bounded to the west by the open Interceptor Canal, to the east by a marginal protection levee, and bisected by

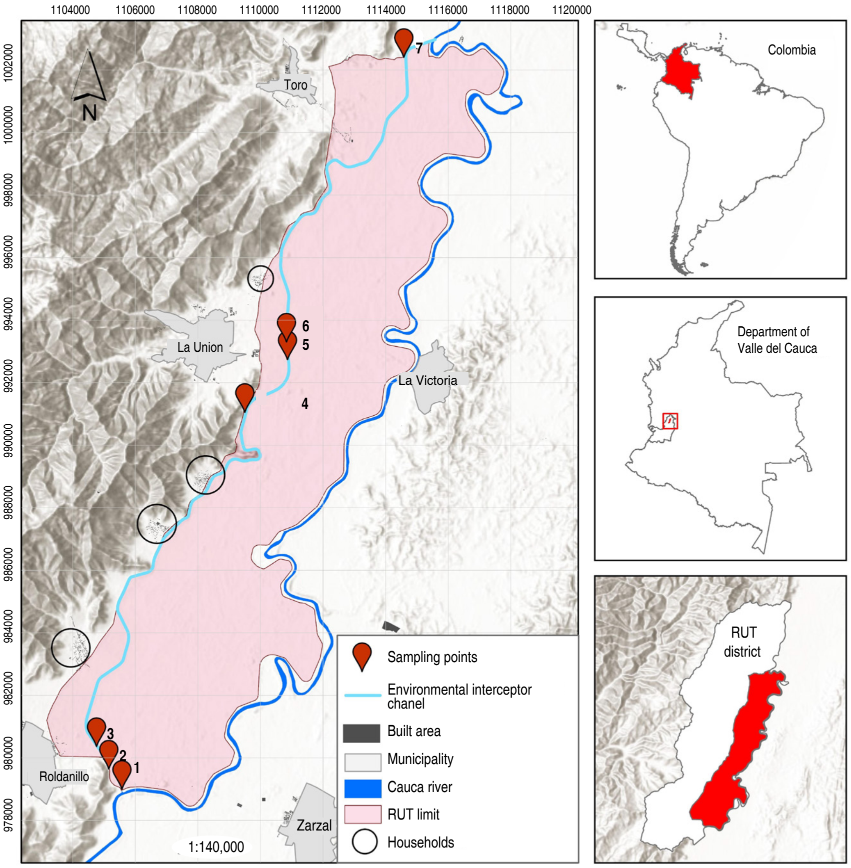


Figure 1. Study site and sampling points in the RUT district.

the Main Drainage Canal. The district is managed by the User Association (ASORUT) and benefits approximately 1,200 farmers (Echeverri-Sánchez et al. 2017). Land use is predominantly sugarcane cultivation (50.4%), followed by maize (14.9%), with smaller areas allocated to chili pepper, soybean, cacao, grape, papaya, melon, guava, passion fruit, and other fruit crops.

Sampling site selection, temporality, and water quality indicators

The seven sampling points were located along the Interceptor Canal of the RUT District (Figure 1). Site selection was based on hydraulic infrastructure, discharge points, and land use characteristics. Additionally, historical precipitation data were used to identify representative sampling periods: November 2021 (high rainfall), June 2022 (low rainfall) and October 2022 (transitional conditions), thereby capturing maximum, minimum, and average hydrological scenarios. The RUT Irrigation District was subdivided into Southern, Central, and Northern zones, corresponding to the municipalities of Roldanillo, La Unión, and Toro, respectively (Table 1).

Table 1. Sampling points description.

Zone	Item	Sampling point	Description
South	1	Tierra Blanca Pumping Station	Located at the outlet of the distribution chamber of the main irrigation water pumping station, immediately after the intake from the Cauca River, at the start of the canal.
	2	Interceptor Canal	Located 1,000 meters from the beginning of the canal, downstream from the discharge of wastewater from households in the Tierra Blanca district, municipality of Roldanillo.
	3	Roldanillo Municipal WWTP Discharge	Located 80 meters downstream from the discharge point of the Roldanillo municipal wastewater treatment plant into the main interceptor canal. The municipality has approximately 32,000 inhabitants and a discharge flow ranging from 30 to 40 L s^{-1}.
Center	4	Portachuelo Pumping Station	Located at km 17+400 of the interceptor canal, downstream from the untreated wastewater discharge of approximately 150 households in the districts of Morelia and Higuerón.
	5	Level Control Structure No. II	Located at km 13+200 of the canal, downstream from the level control structure, near the road connecting the municipalities of La Unión and La Victoria.
	6	La Unión Municipal WWTP Discharge	Located at km 12+500 of the canal, 100 meters from the discharge point of the La Unión municipal wastewater treatment plant. The municipality has approximately 41,000 inhabitants and a discharge flow ranging from 40 to 50 L s^{-1}.
North	7	Toro Municipal WWTP Discharge	Located at km 3 of the canal, next to the downstream level control structure known as Control I, and 50 meters from the discharge point of the Toro municipal wastewater treatment plant. The town has approximately 16,400 inhabitants and a discharge flow ranging from 20 to 40 L s^{-1}.

Evaluation of hazards associated with irrigation water quality

Sampling procedure

Surface water samples were collected as composite samples at all sampling points, following the protocols established by the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM 2002). An aliquot was collected every 20 minutes over a 1-hour sampling period. Samples collected during the first campaign were analyzed by Análisis Ambiental S.A.S., accredited by IDEAM under Resolution No. 0710 of 2019. Samples from subsequent campaigns were analyzed by AGQ Colombia S.A.S., an

IDEAM-accredited laboratory under Resolution No. 1726 of 2022. Table 2 summarizes the analytical methods used by the laboratories to determine the evaluated parameters.

Sampling was carried out by identifying and georeferencing each sampling point using a GPS receiver. Water samples were collected using a calibrated bucket, rinsed prior to each collection, from elevated structures (bridges), which allowed sampling at the center of the canal and at mid-depth of the water column.

For physicochemical analyses, 1-L pre-cleaned plastic containers were used; in the case of hardness determination, sulfuric acid was added as a preservative.

Table 2. Analytical methods used for the determination of irrigation water quality parameters.

Parameter	Method	Uncertainty
ECw (dS m^{-1})	SM 2510 B – Electrometry	±5%
Chlorides (mg L^{-1})	SM 4110 B Mod. Anions – Ion Chromatography	±3.2%
Na^+ (mg L^{-1})	EPA 200.7 Total Metals in Water – ICP-OES	±14.9%
Fe^{2+} (mg L^{-1})	EPA 200.7 Total Metals in Water – ICP-OES	±9.62%
Mn^{2+} (mg L^{-1})	EPA 200.7 Total Metals in Water – ICP-OES	±9.12%
pH	SM 4500 H^+ B – pH in Water – Electrometry	±0.24%
TSS (mg L^{-1})	SM 2540 D Total Suspended Solids (103–105 °C) – Gravimetry	±6.56%
TDS (mg L^{-1})	SM 2540 C Total Dissolved Solids – Gravimetry	±3.1%
Fecal Coliforms (FC) (MPN 100 mL^{-1})	SM 9221 E Fecal Coliforms in Water – MPN	±0.76%

SM: Standard Method; ICP-OES: Inductively Coupled Plasma–Optical Emission Spectrometry; MPN: Most Probable Number.

For fecal coliform analysis, samples were collected in sterilized glass containers with the addition of 0.2 mL of 3% sodium thiosulfate ($Na_2S_2O_3$). All samples were kept under refrigeration and transported to the laboratory for analysis within the established holding times.

Parameter selection

Tables 3 - 6 present the selected hazard types for evaluation, along with the associated parameters, hazard categories, and risk levels. This information was organized based on a review of the scientific literature and criteria established by the authors, as well as relevant studies pertaining to each hazard type.

It should be noted that two methods were selected to evaluate the hazard of soil salinization: one based on the

Table 3. Methods, categories, and levels for estimating the potential impact on soil from the quality of irrigation water.

Parameter	Category	Hazard level		Source
Salinity	ECw (dS m^{-1}) / salt solubility (mmol$_c$ L^{-1})	0 - 0.25/>5000	Low	(Echeverri-Sánchez et al. 2016)
		0-0.25/1000-5000	Low	
		0 - 0.25/<1000	Very low	
		0.25-0.7/>5000	Moderate	
		0.25-0.7/1000-5000	Moderate	
		0.25-0.7/<1000	Low	
		0.7–3.0/>5000	High	
		0.7–3.0/1000-5000	Moderate	
		0.7–3.0/<1000	Moderate	
		>3.0/>5000	Very high	
		>3.0/1000-5000	High	
		>3.0/<1000	High	

Table 3

Parameter	Category	Hazard level		Source
Salinity	ECw (dS m^{-1})	0 - 0.7	Low	(Drechsel et al. 2023)
		0.7–3	Moderate	
		>3	High	
Sodicity	Gypsum requirement (g m^{-3})	0	Very low	(Villafañe 2011)
		0–86	Low	
		86–215	Moderate	
		215–387	High	
		>387	Very high	

FAO guidelines (Drechsel et al. 2023) and another proposed by Echeverri-Sánchez (2016). The FAO methodology classifies the salinity risk of irrigation water solely on the basis of ECw, whereas the approach developed by Echeverri-Sánchez (2016) jointly integrates ECw and salt solubility, the latter estimated according to the methodology proposed by Villafañe (2011). Under this framework, ECw reflects the total amount of dissolved salts present in the water, while salt solubility indicates the ease with which these salts can be leached from the soil through lixiviation processes.

Table 4. Methods, categories, and levels for estimating the potential impact on crops from the quality of irrigation water.

Type of hazard	Parameter	Category	Hazard level	Source
Specific ion toxicity	Chlorides (mg L^{-1})	0–213	Low	(Singh et al. 2020; Tartabull and Betancourt 2016)
		213–355	Moderate	
		>532.5	High	
	SAR (meq L^{-1})	SAR<3	Low	(Drechsel et al. 2023)
		3–9	Moderate	
		SAR>9	High	
	Fe^{2+} (mg L^{-1})	Fe<5.0	Low	(Department of Water Affairs and Forestry 1996; Simsek and Gunduz 2007)
		$5.0 \leq Fe \leq 20.0$	Moderate	
		Fe>20.0	High	
	Mn^{2+} (mg L^{-1})	Mn<0.2	Low	
		$0.2 \leq Mn \leq 10.0$	Moderate	
		Mn>10.0	High	

Table 5. Methods, categories, and levels for estimating the potential impact on irrigation infrastructure from the quality of irrigation water.

Type of hazard	Parameter	Category	Hazard level	Source
Emitter clogging	pH	<6.5	Low	(Department of Water Affairs and Forestry 1996)
		6.5–8.4	Moderate	
		>8.4	High	
	TSS (mg L^{-1})	<50	Low	
		50 a 100	Moderate	
		>100	High	

Table 5

Type of hazard	Parameter	Category	Hazard level	Source
Emitter clogging	TDS (mg L^{-1})	<500	Low	(Department of Water Affairs and Forestry 1996)
		500 a 2000	Moderate	
		>2000	High	
	Mn^{2+} (mg L^{-1})	<0.1	Low	
		0.1 a 1.5	Moderate	
		>1.5	High	
	Fe^{2+} (mg L^{-1})	<0.2	Low	
		0.2 a 1.5	Moderate	
		>1.5	High	
Scaling or corrosion	LSI	<-2	Intolerable corrosion	(Anyango et al. 2024)
		-2 <LSI<-0.5	Severe corrosion	
		-0.5<LSI<0	No scale formation, but slight corrosion	
		LSI=0	Neutral	
		0 <LSI<0.5	Marginal corrosion and scale formation	
		0.5<LSI<2	Non-corrosive with scale formation	

Table 6. Methods, categories, and levels for estimating the potential impact on human health from the quality of irrigation water.

Type of hazard	Parameter	Category	Hazard level	Source
Human health	Fecal Coliforms (FC) (MPN 100 mL^{-1})	<100	Very low	(Adapted Drechsel et al. 2023)
		100-1000	Low	
		1000-10.000	Moderate	
		10.000-100.000	High	
		>100.000	Very high	

Validation of results and hazard estimation

The laboratory results were validated through ion balance estimation and comparison with ECw values (Mageshkumar and Vennila 2020). Once the data were verified—within an acceptable error margin of 15%—the calculation of hazard indicators related to water quality was carried out, as presented in Tables 3 through 6.

RESULTS AND DISCUSSION

Microbiological Hazard

Across the three zones identified, the microbiological hazard associated with FC showed varying levels, evidenced by pronounced differences in median values and P25–P75 ranges (Table 7), with a marked tendency toward a “High” hazard classification at sampling points located downstream from the wastewater treatment plant discharges of the three municipalities (points 3, 6 and 7) (Figure 2). During the second sampling campaign, the highest concentrations were recorded at these points—particularly at point 6, where a “Very High” hazard level was observed with a value of 920,000 MPN 100 mL^{-1}, likely due to the campaign being conducted during a period of lower dilution. This behavior can be explained by the fact that, during dry periods, the flow in the Interceptor Canal is reduced and pumping from the Cauca River is sometimes restricted, thereby increasing the influence of the treatment plant discharges on the system. In addition, these FC concentrations are also attributable to untreated sewage discharged directly into the canal throughout the year from approximately 600 households.

The crops in these zones do not come into direct contact with irrigation water. Notably, sugarcane—the predominant crop—is processed industrially, and its final product undergoes treatments that can enhance food safety (Madera et al. 2009). However, concern remains for fruit crops that are consumed with their peel and for short-stature vegetable crops, as Colombian regulations establish a maximum limit of 1,000 MPN 100 mL^{-1} for fecal coliforms. Non-compliance with these standards compromises food safety and restricts the potential of export-oriented agricultural production.

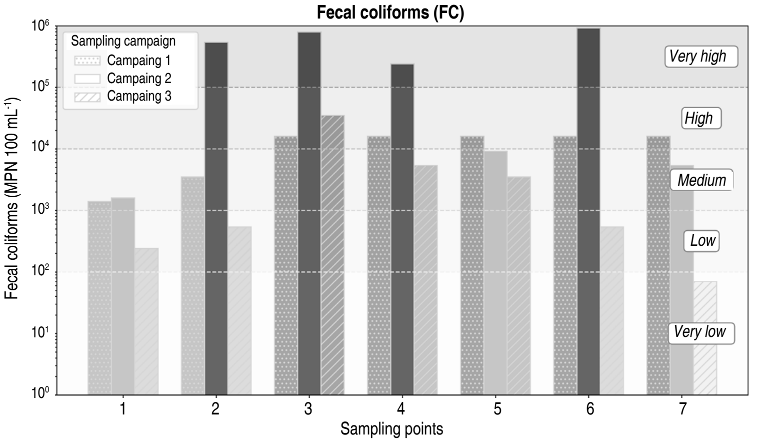


Figure 2. Results of microbiological hazard from FC associated with water quality.

Table 7. Descriptive statistics (median, P25, and P75) of water quality parameters associated with risk categories by monitoring campaign.

Hazard	Parameter	Campaign	Median	P25	P75
Human health	FC (MPN 100 mL^{-1})	1	16,000	9,750	16,000
		2	240,000	7,300	665,000
		3	540.00	390.00	4,450
Soil	ECw (dS m^{-1})	1	0.1	0.11	0.18
		2	0.5	0.29	0.52
		3	0.4	0.16	0.54
	Gypsum requirement (g m^{-3})	1	306	274	328
		2	72	61	210.5
		3	140	68	298
Specific ion toxicity	Chlorides (mg L^{-1})	1	20	20	20
		2	13	7.7	18
		3	12	3.9	19
	SAR	1	0.3	0.1	0.3
		2	0.6	0.4	0.6
		3	0.5	0.3	0.7
Specific ion toxicity / Emitter clogging	Mn (mg L^{-1})	1	0.1	0	0.2
		2	0.4	0.1	0.7
		3	0.5	0.2	0.8
	Fe (mg L^{-1})	1	12	4.9	20.5
		2	1.5	1	2.7
		3	8.5	1.3	19.6
Scaling or corrosion	LSI	1	–1.4	–2.2	–1.3
		2	–0.7	–1.0	–0.4
		3	–0.9	–1.0	–0.3

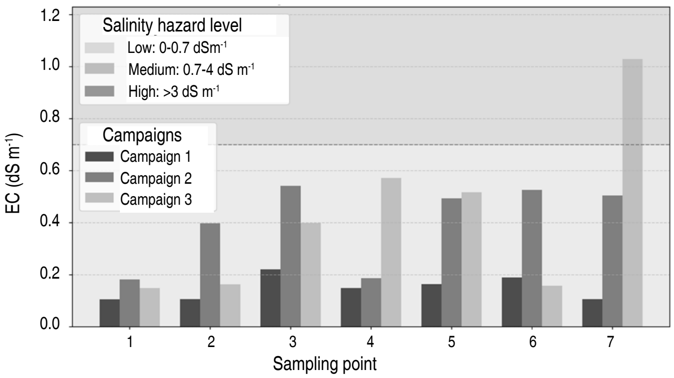
Table 7

Hazard	Parameter	Campaign	Median	P25	P75
Emitter clogging	pH	1	6.7	6.2	6.9
		2	6.9	6.8	7
		3	7.2	7.2	7.3
	TSS (mg L^{-1})	1	285	181.3	3,090.40
		2	53	51.5	293.5
		3	61	46.5	102
	TSD (mg L^{-1})	1	145	75.9	406.8
		2	296	175	309
		3	98	92	326.5

Soil Degradation Hazard

Two different methodologies were applied to evaluate the salinity hazard (Figure 3): the approach proposed by Drechsel et al. (2023) and the method developed by Echeverri-Sánchez (2016). According to the Drechsel et al. (2023) methodology, 95% of the samples analyzed across the three campaigns were classified within the "Very Low" and "Low" hazard categories. The only exception was observed (dS m^{-1}) (Figure 3A). In contrast, Echeverri-Sánchez (2016) method demonstrated greater sensitivity in hazard classification (Figure 3B). Under this approach, 38% of the sampling points increased to a "Moderate" hazard level, while the remaining 57% remained classified as "Low."

A. Ayers and Westcot (1985)



B. Echeverri-Sánchez (2016)

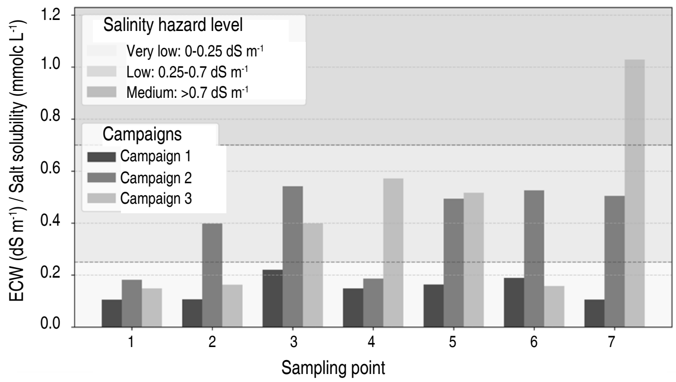


Figure 3. Results of soil salinity hazard associated with irrigation water quality. Background shading indicates salinity hazard classes according to **A**. Ayers and Westcot (1985), and **B**. Echeverri (2016).

Post-sampling analysis revealed that the salinity hazard to soils associated with irrigation water quality increases from “Low” to “Moderate” when moving from the Central Zone toward the Northern Zone of the district. This zone is characterized by gentler slopes, poor drainage, and heavy-textured soils that are prone to physicochemical degradation (Echeverri-Sánchez 2022). Although the solubility of salts in this zone is low (<1,000 mmolc L^{-1}), the ECw of the irrigation water exceeds 1,000 dS m^{-1}.

The pH, generally slightly alkaline and classified as a “Moderate” hazard at the sampling points, indicates a relative reduction of calcium and magnesium in comparison to Na^+ and the SAR. This imbalance promotes the formation of compounds that reduce the availability of essential nutrients for plants (Kundu et al. 2022). Among the common salts detected was NaCl, which may disrupt water uptake and nutrient absorption in plants (Lu and Fricke 2023). Similarly, points 2 and 7 were consistently characterized by the presence of $MgCl_2$, which at high concentrations can significantly impair protein synthesis in plants (Geilfus 2018).

Regarding sodicity hazard (Figure 4), “High” hazard levels were observed, particularly in the Southern Zone, at sampling points 1 and 2, where values exceeded 325 g m^{-3} of pure gypsum required for water treatment (Villafañe 2011). It should be noted that the concentration of this compound exhibited marked contrasts between Campaign 1 and the subsequent campaigns, as the median value in Campaign 1 was approximately twice that observed in the others (Table 7). Nevertheless, data dispersion in Campaign 1 was relatively low, whereas Campaigns 2 and 3 displayed wider interquartile ranges, indicating greater variability during these latter periods. Sodicity leads to the dispersion of soil aggregates, which reduces water infiltration and hydraulic conductivity, and promotes the formation of surface crusts. These conditions hinder root growth and limit the uptake of water and nutrients by plants (Hailu and Mehari 2021).

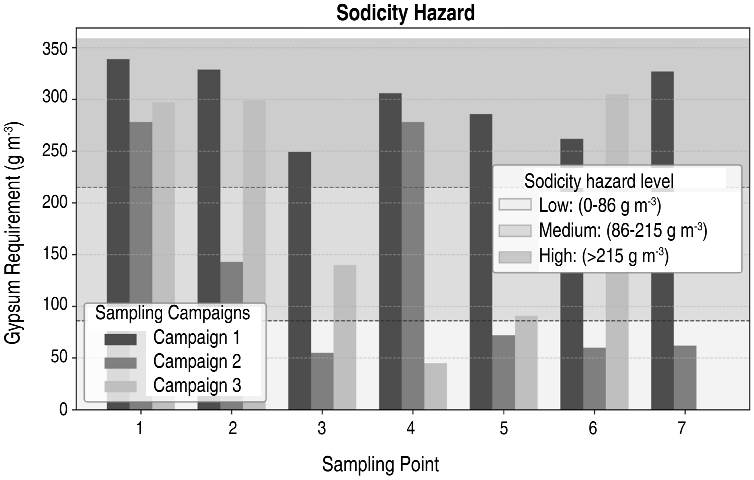


Figure 4. Results of soil sodicity hazard associated with irrigation water quality.

Specific ion toxicity hazard

Results related to specific ion toxicity indicated that Cl^- concentrations were below 213 mg L^{-1}, corresponding to a hazard “Low” level, and that Na^+ values, evaluated using SAR, were lower than 3 meq L^{-1} (Figures 5C and 5D). Consequently, none of these parameters reached levels considered detrimental to the dominant crops in the RUT Irrigation District, as these thresholds correspond to general low-risk conditions for agricultural irrigation according to the reference limits applied.

However, analysis of Fe^{2+} concentrations, based on the adopted risk thresholds (<5 mg L^{-1} low, 5–20 mg L^{-1} medium, and >20 mg L^{-1} high), made it possible to identify sampling points with consistently critical behavior. While Campaign 2 exhibited concentrations within the “Low” hazard range, Campaigns 1 and 3 showed medium-risk conditions, with P75 values approaching or exceeding the “High” hazard threshold, indicating the occurrence of localized critical episodes that do not uniformly affect the entire system (Table

7). Sampling point 1 emerged as the most problematic within the system, recording “High” hazard concentrations during Campaign 1 (24.5 mg L^{-1}) and Campaign 3 (102.0 mg L^{-1}), evidencing the recurrence of severe events with a high likelihood of Fe^{2+} precipitation and emitter clogging. In contrast, sampling points 2 and 4 exhibited concentrations predominantly within the “Medium” or “Low” hazard range, without exceeding the critical threshold, and sampling point 5 consistently remained under “Low” hazard conditions across all campaigns (Figure 5A).

Although soil pH in the RUT District ranges from slightly acidic (pH=6) to slightly alkaline (just above pH=7), this factor alone would not significantly limit Fe^{2+} availability. Nevertheless, the Northern Zone of the district was identified as having poor drainage conditions, which could favor the accumulation of this ion in crops (Lei et al. 2014). Similarly, excess Mn^{2+} may induce toxic effects in plants, manifested as interveinal chlorosis, necrosis in young leaves, and impaired root development (Lee et al. 2011).

Similarly, considering the risk thresholds for Mn^{2+} (<0.2 mg L^{-1} Low, 0.2–10 mg L^{-1} Medium, and >10 mg L^{-1} High), the results show a progressive increase in hazard across campaigns, with median values shifting from predominantly “Low” hazard conditions in Campaign 1 to “Medium” hazard conditions in Campaigns 2 and 3 (Table 3). Sampling points 1 and 2 were identified as the most critical within the system, as they consistently exhibited concentrations within the “Medium” hazard range in all or most campaigns, reaching maximum values of 1.28 and 1.54 mg L^{-1}, respectively (Figure 5B). It should be noted that excess Mn^{2+} may induce toxic effects in plants, manifested as interveinal chlorosis, necrosis in young leaves, and impaired root development (Lee et al. 2011).

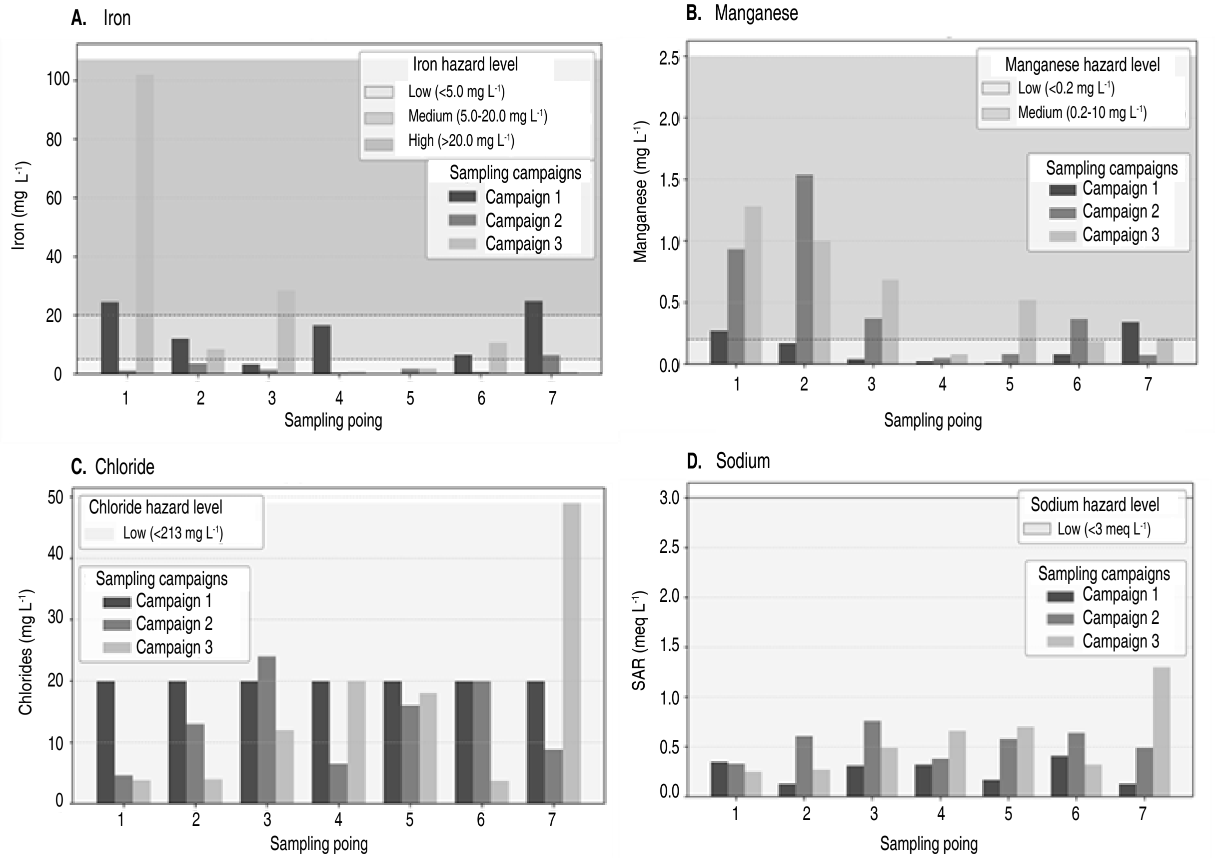


Figure 5. Concentrations of parameters associated with specific ion toxicity hazard: **A**. iron, **B**. manganese, **C**. chlorides, and **D**. sodium, for each sampling campaign.

Scaling, corrosion and emitter obstruction hazard

The LSI was negative in all campaigns, indicating corrosive potential (Figure 6F). Campaign 1 exhibited the highest corrosivity and variability, whereas Campaigns 2 and 3 showed more homogeneous corrosive conditions, as reflected by the median and interquartile range (Table 7).

According to the index classification, 67% of the points fell within the “Severe Corrosion” category, 24% in “No scale formation but slight corrosion,” and 10% in “Intolerable Corrosion.” In Campaign 1, the most negative values were recorded in the Southern Zone at points 1 (-2.92) and 2 (-4.59), indicating intolerable corrosion. In Campaign 2, corrosivity decreased at several points, such as point 5 (-0.17) and point 3 (-0.54). For Campaign 3, hazard levels remained predominantly in the “Severe Corrosion” range. This corrosive trend in the water could primarily affect metallic components (Panday et al. 2021), resulting in hydraulic and economic losses, as well as challenges in the logistics and application of scheduled irrigation volumes. In the western zone of the RUT District—the focus area of this study—drip, sprinkler, and gravity irrigation systems are used, each requiring at least one pumping unit to ensure water delivery due to the low terrain slope. Therefore, this hazard must be considered when selecting equipment or implementing water quality improvement systems on farms.

On the other hand, the hazard of clogging in high-frequency irrigation emitters due to physical parameters revealed that the hazard from TDS was predominantly classified as “Low” (Figure 6A). In contrast, the hazard from TSS showed significant variability in particulate load across campaigns. Campaign 1 registered the highest levels, particularly at point 7 (9,400 mg L^{-1}). In Campaign 2, a drastic reduction was observed at most points, with values below 120 mg L^{-1} except for point 1 (558 mg L^{-1}) and point 7 (473 mg L^{-1}). In Campaign 3, concentration remained low compared to the first campaign, with the lowest recorded value at point 7 in the Northern Zone (23 mg L^{-1}).

The Cauca River water exhibited a “High” hazard level for TSS at point 1 due to its high sediment load, reflected in the elevated sedimentation rate within its canal network. In a section of the Interceptor Canal in the Southern Zone, where two rivers and two streams converge, approximately 12,000 m^3 of sediment are removed quarterly from the canal bed deposited along the canal bank. Downstream from this point, the hazard level decreased to “Moderate,” likely due to a desilting structure located in the main canal that reduces the solid load. This decreasing trend persisted through the Central Zone, but toward the Northern Zone, the hazard level increased again to “High.”

The hazard of clogging in high-frequency emitters due to chemical parameters during Campaign 1 revealed chemically aggressive conditions, with acidic pH values at points 2 (4.03) and 1 (5.71) (Figure 6C), as well as elevated concentrations of Fe^{2+} (Figure 6D) and medium concentration of Mn^{2+} (Figure 6E). In Campaign 2, pH values rose toward neutral, but Mn^{2+} reached its highest concentration (1.53 mg L^{-1} at point 2), maintaining a “High” hazard level. Fe^{2+} concentrations, though still present, were relatively lower, mostly within the “Moderate” hazard range. In Campaign 3, pH stabilized within neutral to slightly alkaline ranges (up to 7.72 at point 7), while Fe^{2+} levels increased critically, reaching up to 102 mg L^{-1} at point 1 and 28.4 mg L^{-1} at point 3, maintaining the “High” hazard classification. These Fe^{2+} concentrations far exceed the recommended thresholds for avoiding encrustation in high frequency localized irrigation systems which are set at concentrations lower than 1.5 mg L^{-1}. Under neutral pH and in the presence of oxygen, Fe^{2+} oxidizes to form $Fe(OH)_3$ precipitates, which can severely clog emitters and conveyance lines (Muniz et al. 2023). These issues can significantly reduce the efficiency of on-farm irrigation systems and lead to high maintenance costs for users.

The results obtained provide a basis for guiding operational measures for irrigation water management according to the main hazard factors identified. TSS concentrations show an increase toward the downstream sampling points, where the risk of emitter clogging becomes more critical; therefore, the implementation of sedimentation and/or pre-filtration processes is recommended to reduce the particulate load. In addition, periodic flushing of pipelines is advised in these areas as a preventive measure. When elevated concentrations of Fe and Mn are recorded, especially at the upstream

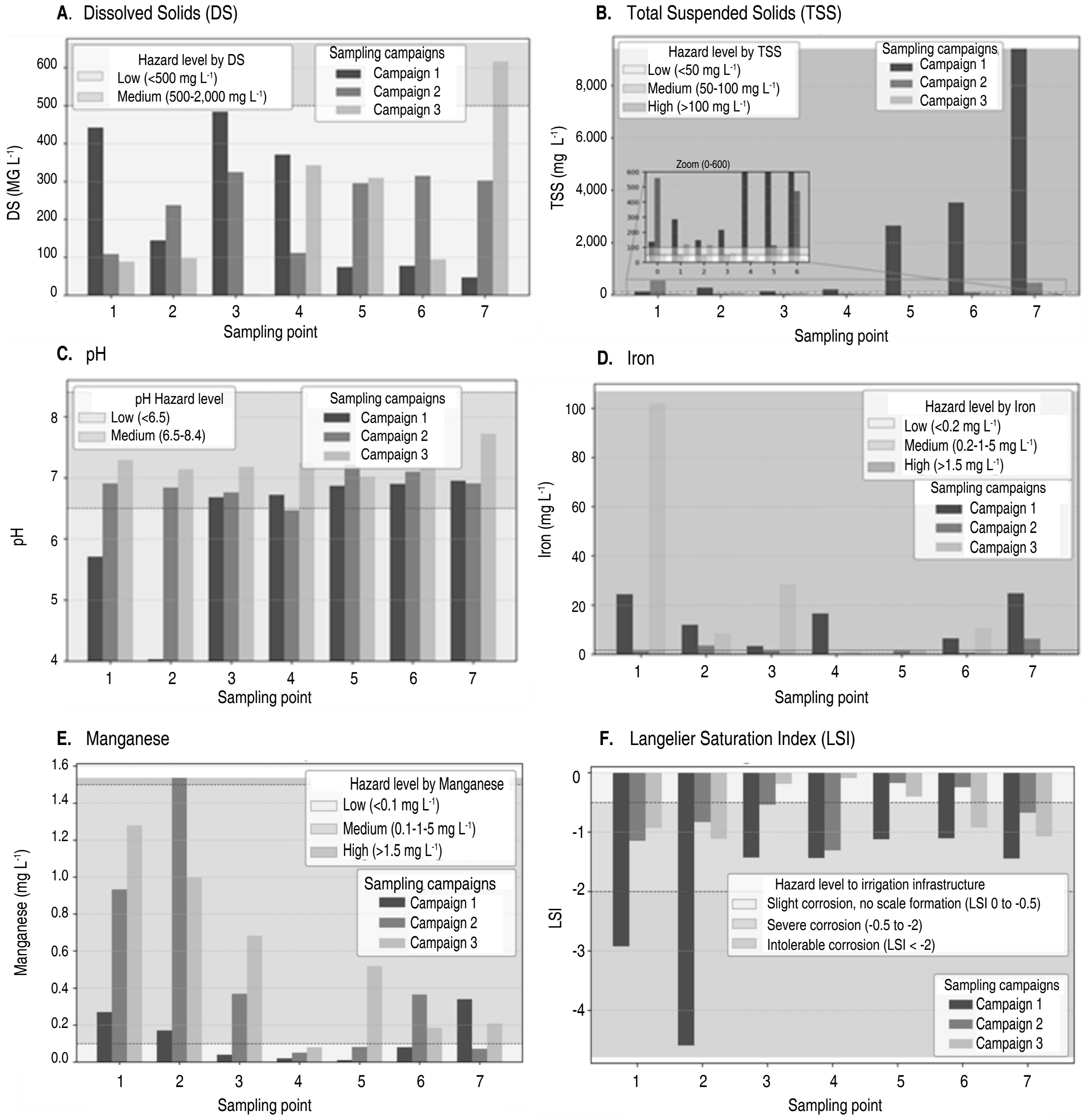


Figure 6. Results of hazards to irrigation infrastructure and emitter clogging associated with **A**. TSS, **B**. total suspended solids, **C**. pH, **D**. iron, **E**. manganese, and **F.** the Langelier Saturation Index.

sampling points, the use of oxidation followed by filtration helps to minimize precipitation and clogging problems. Furthermore, during temporary peaks in ECw, blending with higher-quality water sources can be employed as a strategy to reduce impacts on the irrigation system and the soil.

CONCLUSION

The integrated analysis of water quality in the RUT irrigation district reveals the coexistence of operational, agronomic, and sanitary risks that compromise the sustainability of the system. From an irrigation infrastructure perspective, elevated concentrations of

TSS, Fe^{2+}, and Mn^{2+} imply a "High" hazard of clogging in high-frequency localized irrigation systems and corrosion in components of pumping systems, which may increase maintenance costs and reduce overall hydraulic efficiency. In terms of soils and crops, the presence of Na^+ at critical levels—particularly in the southern zone—suggests an elevated hazard of sodicity, with potential adverse effects on soil structure and agricultural productivity, while Fe^{2+} and Mn^{2+} concentrations could induce moderate toxicity effects in local crops. Likewise, from a human health perspective. The high levels of FC observed across the three zones of the district represent a risk to the safety of horticultural products, food security, and export processes.

These findings underscore the need to strengthen management of the RUT district through continuous monitoring strategies, preventive maintenance of infrastructure, and control measures aimed at reducing the identified risks. In this context, future research should focus on plot- and district-scale studies that assess soil–water–plant interactions, incorporating physicochemical and microbiological variables, as well as analyses of cumulative effects over the medium and long term. Such an approach would support technical and regulatory decision-making, contributing to more efficient and sustainable irrigation management within the district.

ACKNOWLEDGMENTS

The authors would like to thank the ASORUT district for its interest, valuable contributions, and for enabling the development of research related to water quality and reuse within the district's area of intervention. We also extend our gratitude to the REGAR research group from the EIDENAR School at Universidad del Valle for their research ideas and guidance. Likewise, we acknowledge the Water Mirrors Project under the Water and Development Partnership Programme of IHE Delft, funded by the Dutch Ministry of Foreign Affairs (Universidad del Valle Code 21226; IHE Delft Project Number 111305), for providing spaces for discussion and dissemination on the topics addressed.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

REFERENCES

Angelakis AN, Tchobanoglous G, Capodaglio AG and Tzanakakis VA (2024) The importance of nonconventional water resources under water scarcity. Water 16(7): Article 7. https://doi.org/10.3390/w16071015

Anyango GW, Bhowmick GD and Sahoo Bhattacharya N (2024) A critical review of irrigation water quality index and water quality management practices in micro-irrigation for efficient policy making. Desalination and Water Treatment 318: 100304. https://doi.org/10.1016/j.dwt.2024.100304

Ayers RS and Westcot DW (1985) Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29, Rev. 1. Food and Agriculture Organization of the United Nations. https://www.fao.org/4/t0234e/t0234e00.htm

Barona S (2022) Propuesta para la valoración integral de la amenaza de la calidad del agua en riego Estudio de Caso: Subzona Hidrográfica El Guachal - Valle Del Cauca (Tesis de maestría). Universidad del Valle, Santiago de Cali, Colombia.

Drechsel P, Marjani Zadeh S and Pedrero F (2023) Water quality in agriculture: Risks and risk mitigation. FAO & IWMI, Roma. 354 p. https://doi.org/10.4060/cc7340en

Cardona-Almeida C and Suárez A (2024) Integrated water resources management in Colombia: A historical perspective. Ambiente & Sociedade 27: e01187. https://doi.org/10.1590/1809-4422asoc0118r7vu27L1OA

Demerdash DE, Omar MED, El-Din MN et al (2022) Development of a quality-based irrigation water security index. Ain Shams Engineering Journal 13(5): 101735. https://doi.org/10.1016/j.asej.2022.101735

Echeverri-Sánchez A (2022) Methodological proposal to assess the vulnerability of soils to salinization in flan area irrigation districts. Revista Ingenierías Universidad de Medellín 21(40): 28–43. https://doi.org/10.22395/rium.v21n40a3

Echeverri-Sánchez A, Pérez CF, Angulo Rojas PA and Urrutia-Cobo N (2016) A methodological approach for assessing soil salinity hazard in irrigated areas. Case Study: The RUT Irrigation District, Colombia. Revista Ingenierías Universidad de Medellín 15(29): Article 29. https://doi.org/10.22395/rium.v15n29a1

Echeverri-Sánchez A, Angulo-Rojas P, Saavedra-Corredor D, Pérez CF and Urrutia-Cobo N (2017) Assessing soil salinity risk in the RUT Irrigation District, Colombia. Orinoquía 21(Suppl. 1): 76–82. https://doi.org/10.22579/20112629.433

FAO – Food and Agriculture Organization and WHO – World Health Organization (2021) Safety and quality of water used with fresh fruits and vegetables. Microbiological Risk Assessment Series No. 37. Rome. https://doi.org/10.4060/cb7678en

Department of Water Affairs and Forestry (1996) South African Water Quality Guidelines Agricultural Use: Irrigation. Department of Water Affairs and Forestry, Republic of South Africa 4. https://www.dws.gov.za/iwqs/wq_guide/edited/Pol_saWQguideFRESHIrrigationvol4.pdf

Fernandes LS, Galvão A, Santos R and Monteiro S (2023) Impact of water reuse on agricultural practices and human health. Environmental Research 216: 114762. https://doi.org/10.1016/j.envres.2022.114762

Galvis A, Van der Steen P and Gijzen H (2018) Validation of the three-step strategic approach for improving urban water management and water resource quality improvement. Water 10(2):188. https://

doi.org/10.3390/w10020188

Geilfus CM (2018) Chloride: From nutrient to toxicant. Plant and Cell Physiology 59(5): 877–886. https://doi.org/10.1093/pcp/pcy071

Hailu B and Mehari H (2021) Impacts of soil salinity/sodicity on soil-water relations and plant growth in dry land areas: A review. Journal of Natural Sciences Research 12(3):1–10. https://doi.org/10.7176/JNSR/12-3-01

Helmecke M, Fries E and Schulte C (2020) Regulating water reuse for agricultural irrigation: Risks related to organic micro-contaminants. Environ Sci Eur 32:, 4. https://doi.org/10.1186/s12302-019-0283-0

Ingrao C, Strippoli R, Lagioia G and Huisingh D (2023) Water scarcity in agriculture: An overview of causes, impacts and approaches for reducing the risks. Heliyon 9(8): e18507. https://doi.org/10.1016/j.heliyon.2023.e18507

IDEAM - Instituto de Hidrología, Meteorología y Estudios Ambientales (2002) Guía para el Monitoreo de Vertimientos, Aguas Superficiales y Aguas Subterráneas. https://corponor.gov.co/corponor/sigescor2010/EVALUACION%2CSEGUIMIENTO%20Y%20CONTROL/Guia_monitoreo_IDEAM.pdf

Kundu S, Perinjelil SJ and Thakur N (2022) Soil salinization and bioremediation using halophiles and halotolerant microorganisms. pp. 231–256. In: Santoyo G, Kumar A, Aamir M, & Uthandi S (eds.). Mitigation of Plant Abiotic Stress by Microorganisms. 1ª ed. Academic Press, Londres. 428 p.

Lee TJ, Luitel BP and Kang WH (2011) Growth and physiological response to manganese toxicity in Chinese cabbage (*Brassica rapa* L. ssp. *Campestris*). Hortic Environ Biotechnol 52(3):252–258. https://doi.org/10.1007/s13580-011-0224-3

Lei GJ, Zhu XF, Wang ZW, Dong F, Dong NY and Zheng SJ (2014) Abscisic acid alleviates iron deficiency by promoting root iron reutilization and transport from root to shoot in Arabidopsis. Plant Cell Environ 37(4):852–863. https://doi.org/10.1111/pce.12203

Lu Y and Fricke W (2023) Salt stress—regulation of root water uptake in a whole-plant and diurnal context. Int J Mol Sci 24(9):8070. https://doi.org/10.3390/ijms24098070

Madera CA, Silva J, Mara DD and Torres P (2009) Wastewater use in agriculture: Irrigation of sugar cane with effluents from the Cañaveralejo wastewater treatment plant in Cali, Colombia. Environmental Technology 30(10):1011–1015. https://doi.org/10.1080/09593330903020498

Mageshkumar P and Vennila G (2020) Assessment of errors in water quality data using ion balancing methods: A case study from Cauvery River, South India. Indian J Geo-Mar Sci 49(1):57–62. https://www.researchgate.net/publication/339426854

Ministerio de Medio Ambiente y Desarrollo Sostenible (2015) Decree No. 1076 of May 26, 2015: “Decreto Único Reglamentario del Sector Ambiente y Desarrollo Sostenible” [Regulatory Single Decree for the Environment and Sustainable Development Sector]. Diario Oficial No. 49 523. https://www.funcionpublica.gov.co/eva/gestornormativo/norma_pdf.php?i=78153

Muniz GL, Oliveira ALG, Benedito MG, Cano ND et al (2023) Risk evaluation of chemical clogging of irrigation emitters via geostatistics and multivariate analysis in the Northern Region of Minas Gerais, Brazil. Water 15(4): Article 4. https://doi.org/10.3390/w15040790

Panday H, Khanal S, Khatiwada N and Adhikari B (2021) Water corrosion and scale formation problem and its solution in water supply schemes – A case study on Padampokhari and Mahendranagar scheme. Kathmandu University Journal of Science, Engineering and Technology 15(1). https://doi.org/10.3126/kuset.v15i1.63443

Pardo Picazo MÁ, Juárez JM and García-Márquez D (2018) Energy Consumption Optimization in Irrigation Networks Supplied by a Standalone Direct Pumping Photovoltaic System. Sustainability 10(11). https://doi.org/10.3390/su10114203

Shah M, Sircar A, Varsada R, Vaishnani S, Savaliya U et al (2018) Assessment of geothermal water quality for industrial and irrigation purposes in the Unai geothermal field, Gujarat, India. Groundw Sustain Dev 8. https://doi.org/10.1016/j.gsd.2018.08.006

Simsek C and Gunduz O (2007) IWQ Index: A GIS-Integrated Technique to Assess Water Quality Irrigation. Environ Monit Assess 128(1):277–300. https://doi.org/10.1007/s10661-006-9312-8

Singh KR, Goswami AP, Kalamdhad AS and Kumar B (2020) Development of irrigation water quality index incorporating information entropy. Environment, Development and Sustainability 22: 3119–3132. https://doi.org/10.1007/s10668-019-00338-z

Singh S, Ghosh NC, Gurjar S, Krishan G, Kumar S and Berwal P (2018) Index-based assessment of suitability of water quality for irrigation purpose under Indian conditions. Environ Monit Assess 190(1):29. https://doi.org/10.1007/s10661-017-6407-3

Tartabull T and Betancourt C (2016) La calidad del agua para el riego. Principales indicadores de medida y procesos que la impactan. Revista Científica Agroecosistemas 4(1): 47–61. https://aes.ucf.edu.cu/index.php/aes/article/view/75

Villafañe R (2011) Sosalriego: Un procedimiento para diagnosticar los riesgos de sodificación y salinización del suelo con el agua de riego. Bioagro 23(1):57–64. https://ve.scielo.org/scielo.php?pid=S1316-33612011000100008&script=sci_arttext&