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Hydrochemical Assessment of Irrigation Water Quality in Haryana: Implications for Agricultural Sustainability and Future Research

Satish Manda[1]*, Sumit Kumar[1], Ajay Kumar[1], Shubhanjali Kori[2]

[1]Assistant professor, Maharana Pratap Horticultural University Karnal, Haryana, India
[2]Research Scholar, IIT Delhi, New Delhi, India
*Corresponding author: mandastsh@gmail.com

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***Abstract*— *Haryana is one of India's most irrigation-dependent agricultural states, and the quality of irrigation water has become a central determinant to crop productivity, soil sustainability and long-term groundwater security. State-level and regional evidences indicates that irrigation water quality in Haryana is highly heterogeneous, with relatively better water in parts of the north and northeast, and severe salinity, sodium, nitrate, fluoride and chloride problems in substantial parts of the south, southwest, west, and central districts. Recent studies show that groundwater remains usable for irrigation over large areas in the state, but its suitability often depends on crop salt tolerance, soil drainage and other specific parameters like residual sodium carbonate (RSC), electrical conductivity (EC), magnesium hazard (MH) and sodium percentage. This study synthesizes recent evidences on irrigation water quality in Haryana and explains the hydrochemical basis of quality deterioration, evaluates consequences for soils and crops.*

Keywords*— Haryana, irrigation water quality, groundwater, salinity, irrigation suitability, agriculture

Introduction

Irrigated agriculture in Haryana underpins high yields of wheat, rice, mustard, cotton, maize, and horticultural crops. However, this success depends not only on the quantity of water available but also on its chemical quality. In irrigated systems—whether canal-fed or groundwater-based—poor-quality water can reduce infiltration, increase soil sodicity and salinity, disrupt nutrient uptake, and ultimately impair crop performance over time (Jadhav et. al, 2025). This makes irrigation water quality analysis essential for agricultural planning, especially in semi-arid and intensively cultivated regions where groundwater serves as a major buffer against rainfall variability and canal water shortages.

The state of Haryana presents a typical hydro-agricultural contrast, encompassing relatively fresh alluvial groundwater zones, canal-command areas, and extensive tracts where aquifers are affected by salinity and dissolved ions resulting from evaporation, geogenic mineral dissolution, reverse ion exchange, and agricultural or industrial contamination (Malik et al., 2023). A recent study by CCSHAU, Hisar revealed that only 31.83% of Haryana's groundwater falls under the "good quality" category suitable for irrigation of most crops, while 30.04% is marginally saline, 6.04% is saline, 19.50% is high-SAR saline, and 12.59% is sodic or highly sodic water (Mukesh "Only 31% Groundwater"). Despite irrigation suitability being better than drinking-water suitability in many local settings, Haryana remains one of the states with widespread groundwater contamination concerns. It is reported in a recent study that groundwater in several districts of southern, western, and central Haryana is saline or chemically stressed, with notable concerns related to fluoride, nitrate and chloride.

This study was carried out with three major objectives: first, to examine irrigation water quality in the context of Haryana's agro-hydrological conditions; second, to identify suitable hydrochemical parameters for evaluating irrigation water quality, including sodium adsorption ratio (SAR), residual sodium carbonate (RSC), sodium percentage (Na%), Kelly index, and permeability index; and third, to assess the agricultural implications of water quality and its effects on soil health.

Irrigation Infrastructure and Groundwater Reliance in Haryana

Haryana's agriculture is characterized by intensive cultivation, high cropping intensity, and extensive use of both canal water and groundwater for irrigation. In many rural and semi-urban areas, groundwater functions as a major resource where surface water access is inadequate or unreliable, which further increases the importance of understanding its suitability not only for drinking but also for irrigation. The state irrigation and water resources department itself highlights the institutional arrangements linked to water services and dedicated water quality testing laboratories, reflecting the operational importance of water-quality surveillance for water management in the state.

The agronomic significance of irrigation water quality is high in the state because Haryana supports water-demanding cropping patterns alongside growing concerns about aquifer stress and chemical deterioration. In areas where canal supplies are insufficient or spatially uneven, farmers often rely on tubewell water, including in districts where groundwater chemistry is variable. Under such conditions, the same water source may be acceptable for some salt-tolerant crops under well-drained soils but problematic for sensitive crops or poorly drained fields. This conditional suitability is a recurring feature in Haryana: it is reported that most groundwater in the districts of Ambala, Yamunanagar, Sonipat, Panipat, Karnal, and Panchkula is suitable for irrigation for semi-salt-tolerant crops, whereas districts such as Bhiwani, Sirsa, Hisar, Kaithal, Jhajjar, Palwal, and Rohtak show wide variability in irrigation rating. Such variability means that state-level averages can obscure local management risk, reinforcing the need for small-scale or aquifer-zone-scale mapping of irrigation water quality (Kumar et al, 2026).

Irrigation Water Quality: Parameters, Standards, and Agricultural Implications

Irrigation water quality refers to the chemical and physical properties of water that influence its suitability for crop growth, soil health, irrigation infrastructure, and the surrounding agroecosystem. Practically, irrigation suitability is not determined by a single parameter; it emerges from the interaction among various parameters—namely salinity, sodicity, alkalinity, specific ion toxicity, soil texture, drainage conditions, climate, and crop tolerance (Jadhav et. al, 2025) . Consequently, irrigation water that is considered safe in one agroecological setting may produce severe problems in another, underscoring the conditional nature of water quality assessment.

The most commonly used irrigation-water quality indicators include pH, electrical conductivity (EC), total dissolved solids (TDS), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), percent sodium, chloride, bicarbonate, carbonate, nitrate, sulfate, calcium, magnesium, and magnesium hazard (Hemlatha et al., 2025).Each parameter reflects distinct hazards: EC mainly reflects salinity stress, SAR and percent sodium are linked to sodicity and infiltration decline, RSC indicates the tendency for calcium and magnesium precipitation with corresponding sodium hazard amplification, and chloride or boron may cause direct ion toxicity in sensitive crops . In Haryana specifically, RSC, salinity, chloride, fluoride, and nitrate have emerged repeatedly as major parameters of concern in water-quality reporting, particularly in districts where groundwater chemistry is variable.

Modern studies increasingly combine classical hydrochemical indices with spatial analysis, GIS, and composite water-quality indices such as groundwater quality index (GWQI), fuzzy groundwater quality index (FGWQI), or customized irrigation water quality indices (Suryawanshi et al., 2025). These tools are useful for communicating complex datasets to planners, although they should not replace parameter-specific agronomic interpretation because different hazards have different field implications (Gupta et al., 2024). The integration of spatial mapping with traditional indices enables more precise identification of problem zones, allowing for targeted management interventions that account for local soil texture, drainage capacity, and crop tolerance levels.

Hydrochemical Mechanisms Underlying Irrigation Water Quality Degradation in Haryana

Recent studies from southwestern Haryana provide an updated hydrochemical explanation for water-quality deterioration in the state. According to recent findings, the dominant hydrochemical facies include $Ca\text{-}HCO_3$ and Na-Cl types, representing recharge-dominated and salinity-affected conditions, respectively (Kumar et al, 2026). The same study linked water chemistry to water-rock interactions, evaporation dominance, and sodium-calcium reverse ion-exchange processes, with hardness strongly associated with magnesium, chloride, and calcium.

These mechanisms align with the expected scenario in semi-arid alluvial environments experiencing intensive groundwater use. Evaporation concentrates dissolved salts; mineral dissolution contributes calcium, magnesium, bicarbonate, and sulfate; and cation exchange enriches sodium in groundwater, especially when calcium and magnesium precipitate or are exchanged on clay surfaces.

In areas of intensive agriculture, anthropogenic contributions such as fertilizer application, irrigation return flow, and localized wastewater input further elevate nitrate and other ions.

The resulting hydrochemical problems are not uniform across the state. Fresh recharge zones and canal-influenced areas retain relatively lower salinity, while low-drainage or arid tracts with deeper water tables and evaporative concentration may shift toward saline-sodic signatures. This spatial differentiation is crucial for irrigation planning because a single recommendation for all districts is scientifically inappropriate and technically not viable. (Kumari and Rai, 2020)

Water Quality Indices and Parameters for Irrigation Suitability Assessment in Haryana

Research on Haryana's irrigation water quality commonly draws on hydrochemical sampling, laboratory analysis, classification diagrams, and irrigation suitability indices. Laboratory measurements typically include pH, EC, total dissolved solids, major cations and anions, and derived indices such as SAR, RSC, sodium percentage, permeability index, Kelly's ratio, magnesium hazard, and total hardness where relevant. These variables are then interpreted through established irrigation-water criteria and sometimes combined into composite indices.

pH and Alkalinity

The pH of irrigation water influences nutrient availability, carbonate-bicarbonate chemistry, and precipitation reactions in the soil-water system (Pati 539). Although pH alone rarely determines suitability, high alkalinity combined with bicarbonate and carbonate can intensify sodicity problems, especially when calcium and magnesium precipitate out of solution (Schiavon and Moore). In Haryana, this issue is best interpreted through residual sodium carbonate (RSC) rather than pH alone because carbonate chemistry drives the practical hazard for irrigation suitability (Kumari and Rai, 2020). RSC specifically accounts for the imbalance between carbonate/bicarbonate ions and calcium/magnesium, providing a more accurate assessment of sodicity risk than pH measurement alone. RSC has special relevance in northwestern India and particularly in Haryana because bicarbonate-rich waters can precipitate calcium and magnesium, leaving sodium to dominate the soil exchange complex. Reporting based on CGWB assessment found that, statewide, 69.52 percent of groundwater samples were safe for irrigation based on RSC values, 13.09 percent were marginal, and 17.39 percent were unfit for irrigation use. This statistic is one of the most policy-relevant indicators currently available for the state because it directly frames irrigation suitability in terms of a widely used agronomic hazard metric. When RSC values exceed 1.25 me L^{-1}, the water poses moderate to high sodicity hazards that can degrade soil structure and reduce infiltration capacity. The relationship between carbonate alkalinity and divalent cation precipitation is particularly critical in Haryana's semi-arid alluvial aquifers, where evaporative concentration further amplifies the sodicity hazard (Kumar et al., 2026).

Electrical Conductivity and Salinity

Electrical conductivity (EC) is one of the most important irrigation-water indicators because it reflects the total ionic concentration and therefore the salinity hazard imposed on plants and soils. Elevated EC reduces the osmotic potential of soil solution, making it harder for plants to extract water even when the soil appears moist. Reporting From CGWB related data for Haryana highlighted that groundwater in several districts is saline and that at locations where EC exceeds 5000 µS/cm, such water is not suitable for regular irrigation. The salinity of water is checked through its electrical conductivity, where low conduction shows low salinity, while high salinity was found scattered in Bhiwani, Faridabad, Gurgaon, Hisar, Jhajjar, Kaithal, Mahendergarh, Mewat, Palwal, Rewari, Rohtak, Sirsa, and Sonepat districts.

Sodium Hazard and SAR/Percent Sodium

High sodium relative to calcium and magnesium degrades soil structure by dispersing clay particles, reducing aggregate stability, and decreasing infiltration and hydraulic conductivity. Recent Haryana research indicates that isolated zones with elevated percentage of sodium may create sodicity and permeability risks even when broader regional irrigation suitability seems acceptable. Approximately 19.50% of Haryana's groundwater is classified as high-SAR saline water, while 5.67% is slightly sodic, 1.66% is sodic, and 5.26% is highly sodic. It is important because a water source that appears only moderately saline may still be damaging if its sodium proportion is high.

Chloride, Nitrate, and Fluoride

Although chloride, nitrate, and fluoride are often discussed primarily in the context of drinking-water safety, they also matter for irrigation systems. Chloride contributes to salinity and can produce specific toxicity in sensitive crops, nitrate can indicate agricultural contamination and alter nutrient balances, and fluoride may accumulate in certain soils or affect overall water-use desirability. In Haryana, high fluoride and nitrate have been repeatedly reported in multiple districts, while chloride concentrations above 1000 mg/L have been observed in isolated locations in Sirsa, Hisar, Bhiwani, Mahendragarh, Mewat, Jhajjar, and Rohtak (CGWB 2022-23).

Magnesium hazard and permeability risks

The recent study for southwestern Haryana reported that isolated zones elevated magnesium hazard may pose irrigation concerns even where the majority of samples remain broadly suitable. Excess magnesium relative to calcium can worsen soil physical conditions and complement sodium-related structural decline in certain settings. For Haryana's fine-textured alluvial soils, this interaction deserves closer field validation because permeability loss can reduce irrigation efficiency and exacerbate secondary salinization.

Regional Disparities in Irrigation Water Quality and Associated Constraints in Haryana

Studies support a strong regional pattern in Haryana's irrigation water quality. Northern and northeastern districts such as Ambala, Yamunanagar, Karnal, Panchkula, Panipat, and Sonipat generally have better irrigation ratings, at least for semi-salt-tolerant crops on adequately drained soils, contrasting with southwestern, western, and some central districts showing much greater variability and persistent chemical stress (Ramprakash et al, 2023). The groundwater quality in north-eastern Haryana (Yamunanagar and Ambala) is predominantly '$Ca–Mg–HCO_3–Cl$' type, indicating relatively fresh recharge water.

The most commonly mentioned problem districts include Sirsa, Fatehabad, Hisar, Jind, Jhajjar, Bhiwani, Mewat/Nuh, Mahendragarh, Rewari, Faridabad, Palwal, Rohtak, and Kaithal, although the nature and degree of hazard differ among them. In these districts, salinity, RSC, nitrate, fluoride, and chloride occur in various combinations, and therefore suitability must be analysed parameter by parameter rather than through a single contamination label. Recent peer-reviewed work highlighted southwestern Haryana as a region where hydrochemical complexity is driven by both geogenic and anthropogenic processes (Kumar et al.).

By Evaluating all the scenarios, it can be inferred that Haryana contains three broad irrigation-water quality zones which are relatively favourable fresh-water zones, transitional mixed-quality zones, and saline/sodic risk zones. The boundaries between these zones are not administrative; they reflect hydrogeology, recharge conditions, canal influence, land use, and local management history. Therefore, district averages should not substitute for site-specific testing.

Soil and Crop Responses to Poor-Quality Irrigation Water

Soil Salinization and Sodification

The most serious long-term effect of poor-quality irrigation water is the gradual salinization and sodification of agricultural soils. Saline irrigation water increases the salt load in the root zone, while sodic water or water with high residual sodium carbonate (RSC) degrades soil structure by promoting clay dispersion, crusting, poor infiltration, and reduced aeration. In semi-arid regions, these effects intensify where natural leaching is limited and drainage is inadequate.

Crop Response and Yield Stability

Crop performance under poor-quality irrigation water depends on species, cultivar salt tolerance, growth stage, soil type, and management practices. Studies indicate that much of the groundwater in Haryana can still support crops such as wheat, mustard, rice, barley, and maize on well-drained soils, particularly when these crops are relatively salt tolerant. This does not mean that water-quality constraints are agronomically harmless; rather, it shows that farmers may maintain production under marginal water conditions by relying on tolerant crops and favourable field conditions (Choudhary and Mavi,2023).

Nutrient Imbalance and Soil Health Decline

High bicarbonate, sodium, chloride, and nitrate loads can alter nutrient availability and root-zone chemistry. Over time, degraded soil physical structure reduces fertilizer-use efficiency, hampers seedling emergence, and increases the energy cost of tillage and irrigation. These effects are especially relevant in Haryana's intensive cereal systems, where repeated use of marginal groundwater can create chronic rather than acute productivity loss.

Irrigation Efficiency and Infrastructure Effects

Poor-quality water can reduce irrigation efficiency by lowering infiltration, increasing surface sealing, and causing uneven wetting patterns in the field. In pressurized irrigation systems, dissolved solids and precipitation risks may also contribute to clogging or maintenance burdens, particularly where water treatment is inadequate. These issues matter not only for water-saving technologies but also for Haryana's broader push toward more efficient irrigation practices under growing water scarcity.

CONCLUSION

The quality of irrigation water in Haryana is best understood as a spatially heterogeneous and agronomically conditional resource rather than as a uniformly safe or unsafe input. Large parts of the state continue to use groundwater successfully for agriculture, but district- and site-specific hazards related to salinity, residual sodium carbonate, sodium dominance, nitrate, chloride, and fluoride remain significant.

For Haryana's future agriculture, the central challenge is not merely to expand irrigation access but to align water use with water quality and it requires routine monitoring, parameter-specific interpretation, localized advisory systems, crop planning based on quality constraints, conjunctive water use, drainage support and regulation of pollution sources. A robust research agenda for Haryana must integrate hydrochemical characterization, agronomic profiling, soil physical–chemical diagnostics, and high-resolution geospatial analytics to generate district-level, crop-specific guidelines for sustainable irrigation management. Such a multidisciplinary framework will enable precision targeting of water-quality mitigation strategies, optimize crop–water–soil interactions, and ensure long-term productivity of the state's intensive cereal systems under escalating water-scarcity and quality constraints.

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