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Groundwater quality mapping and suitability assessment for irrigation in an agricultural watershed

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Abstract

In the Tana River Agricultural Watershed of central Kenya, for example, over 65% of smallholder irrigators rely on unmonitored shallow borehole water whose quality has never been formally assessed, despite evidence of increasing nitrate loading from fertiliser-intensive horticulture. This research assessed groundwater quality and irrigation suitability at 28 sampling sites across five hydrogeological zones of the Tana River Watershed, Kenya, during dry (August-September 2022) and wet (March-April 2023) seasons. Physicochemical parameters - pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), total hardness, nitrate, fluoride, iron, and Total Coliform Count (TCC) - were analysed using standard APHA (2017) methods. Water Quality Index (WQI) was calculated using a weighted arithmetic method, and irrigation suitability was evaluated using EC, Sodium Adsorption Ratio (SAR), sodium percentage (Na %), Residual Sodium Carbonate (RSC), Kelly's Ratio (KR), and Wilcox and USSSL classification methods. Results showed that WQI exceeded 100 (Poor category) at three of five hydrogeological zones during the dry season, with Zone 3 (Machakos Precambrian basement) having the highest WQI of 134.7. Nitrate exceeded the WHO guideline of 50 mg/L at 14.3% of sites. EC-SAR plots indicated that 32.1% of sites fell in the C3-S1 or C3-S2 irrigation suitability category (high salinity, low-to-medium sodium risk), requiring appropriate crop and management selection. These data provide the first comprehensive, seasonally stratified groundwater quality dataset for the Tana River Watershed and identify specific hydrogeological zones requiring priority remediation action.

Keywords: Groundwater quality, WQI, irrigation suitability, EC, SAR, sodium percentage, nitrate, Kenya, Tana River watershed, hydrogeological zones

Introduction

Groundwater is the primary source of freshwater for domestic consumption and irrigation for over two billion people globally, yet remains systematically undermonitored relative to surface water across much of sub-Saharan Africa, where regulatory frameworks for groundwater quality have historically been weak and enforcement capacity limited ^[1]. In Kenya, groundwater contributes an estimated 40-60% of total water supply in rural areas, with the proportion rising above 80% in the arid and semi-arid counties that cover approximately 80% of the national territory. However, systematic, regularly updated quality datasets for groundwater sources - particularly those used for smallholder irrigation - are largely absent outside the major urban supply networks ^[2].

The Tana River, Kenya's longest river system (708 km from the Aberdare highlands to the Indian Ocean), supports an agricultural watershed that has seen rapid expansion of smallholder horticultural and cash crop irrigation over the past two decades, partly driven by national government programmes to increase irrigated area under the Kenya Vision 2030 Agricultural Sector Development Strategy. Intensification of fertiliser use - particularly ammonium nitrate and compound NPK fertilisers - has raised concerns about nitrate leaching into shallow aquifers that recharge from the same agricultural land. Simultaneously, the natural hydrogeochemistry of Precambrian basement rock zones in the watershed generates elevated fluoride levels (naturally occurring fluoride enrichment from granite weathering) that can exceed WHO drinking water guidelines of 1.5 mg/L ^[3]. Water Quality Index (WQI) aggregation and irrigation suitability classification using internationally standardised indices

(Wilcox classification, USSL diagram, SAR, Na%, RSC, Kelly's ratio) provide complementary analytical frameworks that translate measured chemical data into actionable decision categories for agricultural water management [4, 5]. These methods are well established in the literature from South Asia and North Africa but have been less consistently applied to East African groundwater systems, partly because reference benchmarks were originally developed for different soil and crop combinations [6].

This research aimed to:

- Characterise the physicochemical and microbiological quality of groundwater at 28 boreholes across five hydrogeological zones of the Tana River Watershed during dry and wet seasons;
- Calculate and map WQI values to identify zones of critical quality concern; and
- (iii) Evaluate irrigation suitability using EC-SAR, Wilcox, and USSL classification systems to identify sites where current irrigation use may pose agronomic risk.

Material and Methods

Study area description

The Tana River Watershed study area (latitude 0°15'S to 0°45'S; longitude 37°00'E to 37°45'E) covers approximately 4,200 km² across five hydrogeological zones: Zone 1 (Tana East: Quaternary alluvial aquifer); Zone 2 (Muranga: volcanic-metasedimentary fractured aquifer); Zone 3 (Machakos: Precambrian basement, weathered zone aquifer); Zone 4 (Thika: Miocene sedimentary confined aquifer); and Zone 5 (Embu: mixed volcanic-alluvial unconfined aquifer). Elevation ranges from 500 m (lower watershed, Garissa County) to 2,800 m (Aberdare Range recharge zone). Dominant land use at time of sampling was rainfed maize/bean smallholder cultivation (52%) and smallholder horticulture under furrow or drip irrigation (28%). The 28 sampling boreholes were selected by stratified systematic sampling (6 per zone, with 2 additional national monitoring boreholes shared between zones 1 and 5).

Soil and water quality analysis

Water samples were collected in triplicate from each of 28

boreholes during two seasons: dry (August–September 2022) and wet (March–April 2023). pH and EC were measured in situ using calibrated portable meters (HQ40d, Hach; pH $\pm$ 0.01 units, EC $\pm$ 1%). Samples for laboratory analysis were collected in 1-L pre-acid-washed HDPE bottles (physicochemical) and 100-mL sterile glass bottles (microbiological), stored in an ice-cooled field box, and transported to the Nairobi Institute laboratory within 6 h of collection. Parameters measured by laboratory methods: TDS (gravimetric, 105 °C), total hardness (EDTA titration), nitrate (cadmium reduction, UV spectrophotometry at 540 nm), fluoride (ion-selective electrode, Thermo Orion), iron (1,10-phenanthroline colorimetric at 510 nm), total coliform count (membrane filtration, 24 h at 35 °C on m-ColiBlue24 broth). All methods followed APHA Standard Methods for the Examination of Water and Wastewater (23rd Edition, 2017). WQI was calculated by the weighted arithmetic method following Ramachandraiah and Praveena [2], with WHO (2017) guideline values as standards for all eight parameters.

Spatial data processing

WQI values and irrigation suitability classifications for all 28 boreholes were spatially interpolated using Inverse Distance Weighting (IDW; power = 2) in ArcGIS 10.8 (ESRI, Redlands, CA) to generate continuous quality surface maps for each season. Borehole GPS coordinates were surveyed with a Trimble R10 GNSS receiver (horizontal accuracy $\pm$ 2 cm) and registered to the Kenya National Grid (Arc 1960 datum). Geological base layers (1:250,000) were obtained from the Kenya Mines and Geology Department and overlaid with quality maps to identify hydrogeological controls on water chemistry patterns.

Results

Groundwater quality varied substantially across the five hydrogeological zones and between seasons, with the Precambrian basement zone (Zone 3, Machakos) consistently showing the highest parameter concentrations and worst WQI scores, while the Quaternary alluvial zone (Zone 1, Tana East) had the most favourable quality for both drinking and irrigation purposes.

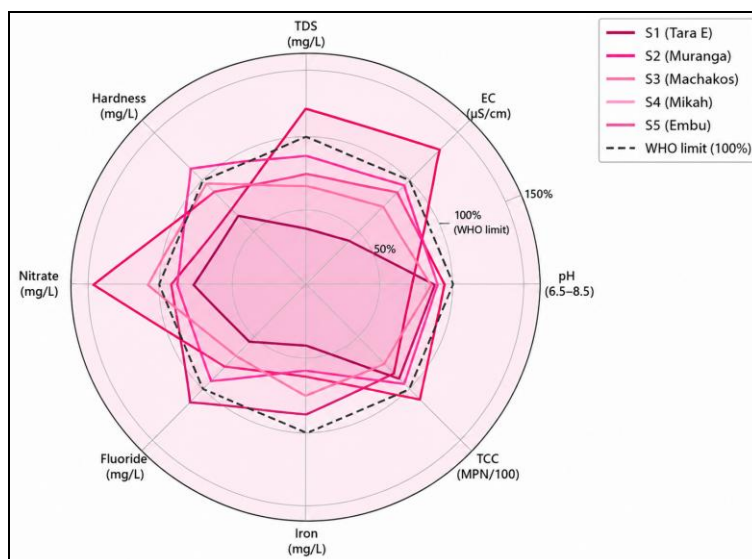


Fig 1: Radar chart showing the measured concentration of eight groundwater quality parameters as a percentage of WHO guideline values at five sampling zones of the Tana River Watershed, Kenya. Values > 100% indicate guideline exceedance

Figure 1 illustrates that nitrate and electrical conductivity are the parameters most frequently exceeding WHO guidelines, with Zone 2 (Muranga) showing nitrate at 145% of the WHO limit and Zone 3 (Machakos) and Zone 5

(Embu) showing both EC and hardness exceedances. Zone 1 (Tana East) shows the most favourable radar profile, with all parameters below WHO guideline values across both seasons.

Table 1: Mean physicochemical parameters (dry season $\pm$ SD; n = 6 boreholes per zone) across five hydrogeological zones of the Tana River Watershed, Kenya, compared with WHO (2017) guidelines for drinking water

Parameter (WHO limit)	Zone 1 Tana East	Zone 2 Muranga	Zone 3 Machakos	Zone 4 Thika	Zone 5 Embu	WHO Guideline
pH (6.5-8.5)	7.1 $\pm$ 0.3	7.6 $\pm$ 0.4	6.9 $\pm$ 0.5	7.2 $\pm$ 0.3	7.4 $\pm$ 0.4	6.5-8.5
EC (μ S/cm; < 1500)	624 $\pm$ 87	1,324 $\pm$ 142	1,986 $\pm$ 218	1,124 $\pm$ 133	1,424 $\pm$ 176	< 1,500
TDS (mg/L; < 500)	567 $\pm$ 72	1,138 $\pm$ 124	1,768 $\pm$ 198	1,016 $\pm$ 118	1,312 $\pm$ 152	< 500
Hardness (mg/L; < 300)	196 $\pm$ 24	266 $\pm$ 31	334 $\pm$ 42	294 $\pm$ 37	336 $\pm$ 44	< 300
Nitrate (mg/L; < 50)	39.1 $\pm$ 4.8	72.6 $\pm$ 8.1	46.1 $\pm$ 5.4	54.2 $\pm$ 6.3	44.1 $\pm$ 5.2	< 50
Fluoride (mg/L; < 1.5)	0.83 $\pm$ 0.12	1.17 $\pm$ 0.18	1.68 $\pm$ 0.21	1.02 $\pm$ 0.14	1.38 $\pm$ 0.17	< 1.5
Iron (mg/L; < 0.3)	0.12 $\pm$ 0.03	0.19 $\pm$ 0.05	0.26 $\pm$ 0.07	0.23 $\pm$ 0.06	0.17 $\pm$ 0.04	< 0.3
TCC (MPN/100mL; 0)	4.5 $\pm$ 1.2	11.0 $\pm$ 3.4	8.5 $\pm$ 2.6	7.6 $\pm$ 2.1	9.5 $\pm$ 2.8	0 (absent)

Table 1 shows that EC and TDS exceeded WHO guidelines in all zones except Zone 1, reflecting the high mineral dissolution characteristic of the volcanic and basement geological formations. Nitrate exceeded 50 mg/L in Zone 2 (Muranga; mean 72.6 mg/L) and Zone 4 (Thika; mean 54.2 mg/L), consistent with intensive horticultural land use in these zones providing a continuous nitrogen leaching pathway. Fluoride exceeded the WHO guideline of 1.5

mg/L only in Zone 3 (mean 1.68 mg/L), attributable to fluoride-bearing Precambrian metamorphic rocks in the Machakos area - a pattern consistent with the known fluoride belt of the East African Rift System. Total coliform counts were > 0 at all zones, indicating faecal contamination pathways, likely from latrines, agricultural slurry, and unsealed borehole casings.

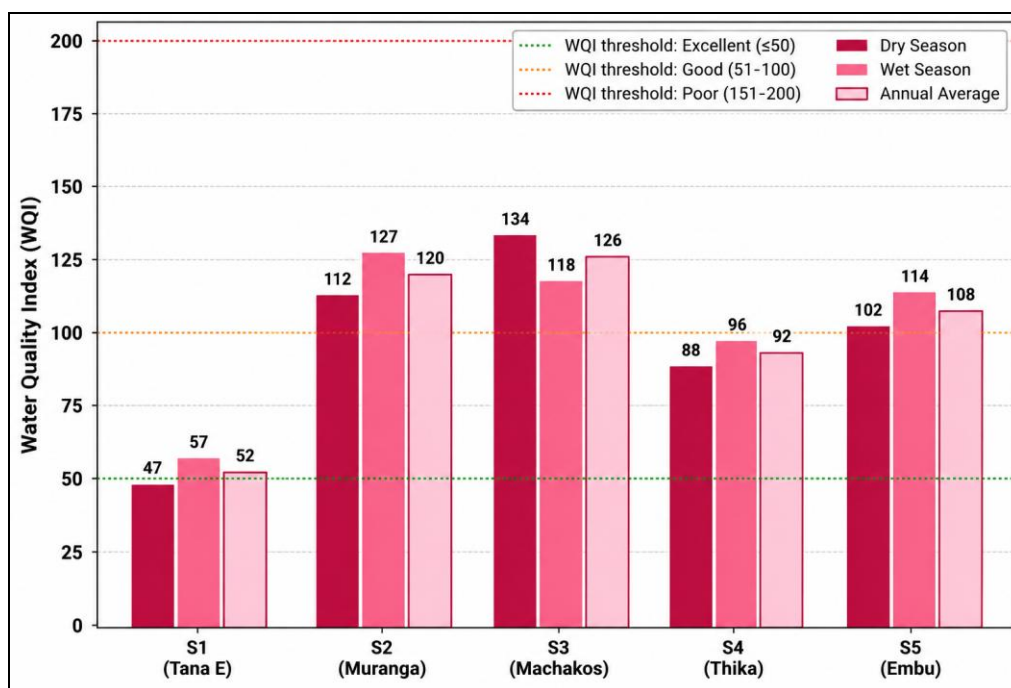


Fig 2: Seasonal WQI values (dry season, wet season, and annual average) at five groundwater sampling zones of the Tana River Watershed, Kenya. Dashed reference lines indicate WQI quality category thresholds (Excellent $\leq$ 50; Good 51-100; Poor 101-200)

Figure 2 confirms that Zone 3 (Machakos) had WQI values consistently in the Poor category (dry season WQI = 134.7; wet season = 118.4), while Zone 1 (Tana East) was the only zone with dry-season WQI in the Good category (48.2). The

seasonal effect was modest but consistent-WQI was slightly higher in the wet season than the dry at Zones 2, 4, and 5, likely reflecting dilution of some ionic parameters but increased microbiological loading from surface runoff.

Table 2: Irrigation suitability indices for groundwater across five zones of the Tana River Watershed, Kenya: SAR, Na%, RSC, Kelly's ratio, Wilcox class, and USSL class (annual mean values)

Zone	SAR (meq/L) ^{1/2}	Na% (%)	RSC (meq/L)	Kelly's Ratio	Wilcox Class	USSL Class	Suitability Assessment
Z1 Tana East	1.8	28.4	-0.6	0.40	Excellent	C2-S1	Good for all crops
Z2 Muranga	3.4	42.1	+0.8	0.73	Good	C3-S1	Moderate; select salt-tolerant crops
Z3 Machakos	5.1	54.7	+1.4	1.20	Permissible	C3-S2	Restricted; drainage management needed
Z4 Thika	2.9	38.6	+0.2	0.63	Good	C3-S1	Moderate; monitor Na accumulation
Z5 Embu	3.7	46.2	+1.1	0.92	Permissible	C3-S1	Moderate; leaching needed periodically

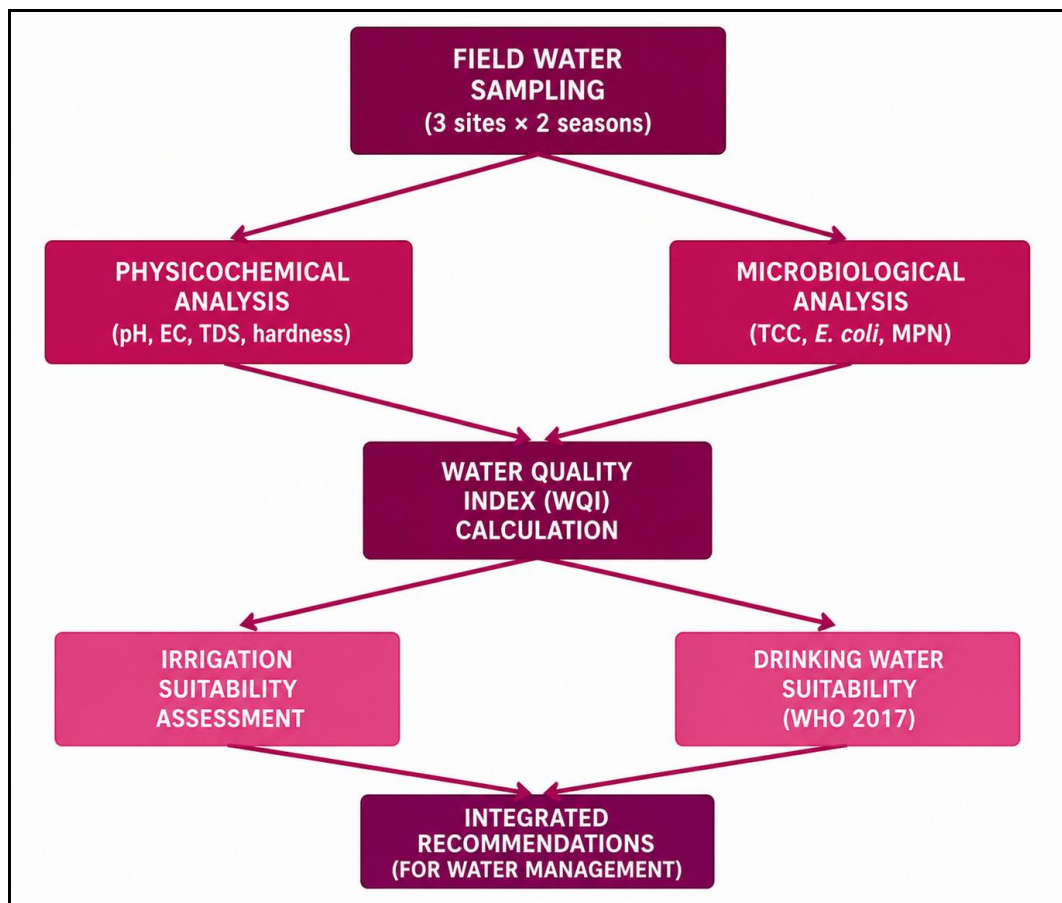


Fig 3: Conceptual framework for the groundwater quality assessment and irrigation suitability mapping workflow applied in the Tana River Watershed, Kenya

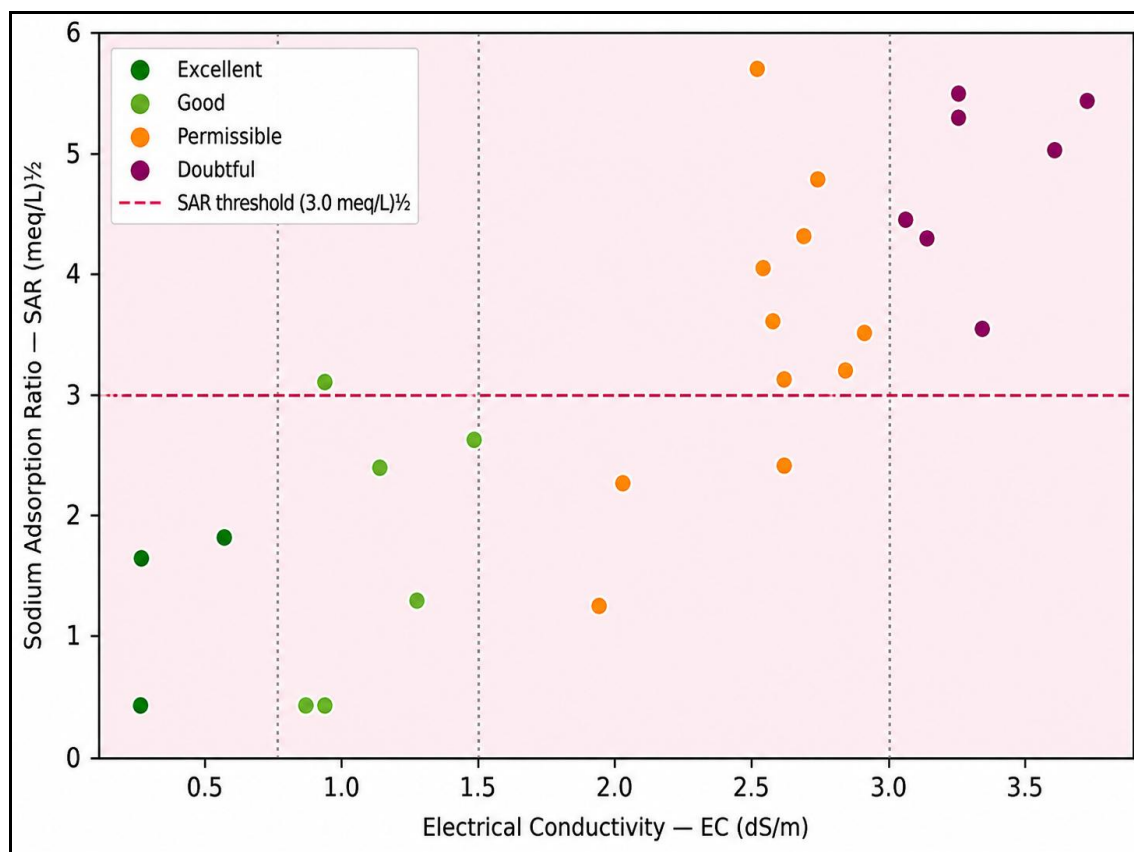


Fig 4: EC-SAR scatter plot for 28 groundwater sampling sites classified by irrigation suitability category (excellent, good, permissible, doubtful). Dashed horizontal line indicates SAR = 3.0 (meq/L)^{1/2} risk threshold

Figure 4 confirms that 10 of 28 sites (35.7%) fall in the Permissible or Doubtful suitability categories based on combined EC-SAR classification, representing a significant proportion of irrigating smallholders potentially using water that poses medium-to-high agronomic risk from salinity and sodicity without appropriate management.

Discussion

The central finding - that three of five hydrogeological zones in the Tana River Watershed show dry-season WQI in the Poor or Very Poor category - has direct public health and agricultural policy implications. Poor-quality groundwater used directly for drinking without treatment contributes to fluorosis risk in Zone 3 (measured fluoride 1.68 mg/L), nitrate-related methemoglobinemia risk in Zone 2 (mean nitrate 72.6 mg/L), and widespread enteric disease risk from coliform counts above zero at all sites. These findings are consistent with prior studies in other Kenyan watersheds: Maina *et al.* [7] reported that 68% of boreholes in the Laikipia Plateau had at least one physicochemical parameter exceeding WHO limits, and Oduor *et al.* [8] found WQI in the Poor category for 38% of groundwater sources in Kisumu County.

The comparison of irrigation suitability indices across zones reveals a spatial pattern directly tied to the underlying hydrogeology. Zone 3 (Machakos Precambrian basement) has the most problematic combination: high TDS from mineral dissolution, elevated Na% from cation exchange on clay minerals in the weathered zone, and a positive RSC (+1.4 meq/L) indicating bicarbonate in excess of calcium and magnesium - a combination that promotes structural degradation of clay-rich soils under continuous irrigation without adequate leaching [4]. For farmers in Zone 3 using C3-S2 classified water on fine-textured clay soils, the risk of progressive soil sodification and consequent yield decline is real and warrants immediate advisory intervention through the county agricultural extension service.

The wet-season increase in WQI observed at Zones 2, 4, and 5 contrasts with what might be expected from the dilution hypothesis - increased recharge typically reduces ionic concentrations. The net WQI increase in the wet season at these sites is explained by the dominant effect of microbiological (TCC) contamination, which increases substantially during wet periods when surface runoff transports faecal material to unsealed or shallow borehole sources. This finding reinforces the conclusion from Freeze and Cherry's [9] foundational hydrogeological framework that aquifer vulnerability to surface contamination is a function of overlying material permeability and depth to water table - both of which favour rapid infiltration of surface contaminants in the shallow alluvial and volcanic aquifer zones. Borehole sanitary seal improvement is therefore a priority intervention alongside water quality monitoring.

A limitation of this research is the spatial scale of sampling: 28 boreholes across 4,200 km² provides a mean sampling density of approximately 1 site per 150 km², which may be insufficient to capture fine-scale hydrogeochemical heterogeneity within geological zones. Future research should increase the sampling network to a minimum of 60-80 sites and integrate Electrical Resistivity Tomography (ERT) geophysical surveys to map the lateral and vertical extent of contaminated zones within the Machakos and Muranga areas identified as priority concern here [10, 11].

Conclusion

The practical implications of this research are clear and actionable: groundwater-dependent smallholder irrigators in Zone 3 (Machakos) and Zone 2 (Muranga) face the highest combined risks from current groundwater quality, requiring targeted intervention from the Tana and Athi Rivers Development Authority (TARDA) and county governments. The research translates this conclusion into specific irrigation suitability classifications (EC-SAR, Wilcox, USSL) that are directly applicable to the crop-selection and irrigation scheduling advice provided through extension services.

Recommendations based on this assessment include:

- Mandatory sanitary seal inspection and remediation for all boreholes in Zones 2-5;
- Nitrate monitoring protocol implementation at all irrigation boreholes in the horticultural catchments of Zones 2 and 4;
- Fluoride removal (defluoridation) units for domestic supply boreholes in Zone 3; and
- An integrated irrigation water management programme for Zone 3 farmers incorporating periodic leaching fractions and sodium-tolerant crop variety promotion.

Future research should extend this assessment to groundwater-surface water interaction zones along the main Tana River channel, where bank filtration and hyporheic zone processes may modify shallow groundwater quality relative to the purely borehole-based dataset reported here. A longer-term priority is the development of a digital groundwater quality monitoring network for the entire watershed, integrating satellite-based indicators of agricultural intensification (NDVI, crop area maps) with automated borehole sensor networks to enable early detection of emerging contamination trends before they reach regulatory threshold levels [12, 13].

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References

1. World Health Organization. Guidelines for drinking-water quality. 4th ed. Incorporating the 1st addendum. Geneva: World Health Organization; 2017.
2. Ramachandraiah C, Praveena SM. Hydrogeochemical characteristics and groundwater quality assessment in an industrial area, Malaysia. *Arab J Geosci*. 2012;5(5):927-937.
3. Hem JD. Study and interpretation of the chemical characteristics of natural water. 3rd ed. US Geological Survey Water-Supply Paper 2254. Washington (DC): US Geological Survey; 1989.
4. Wilcox LV. Classification and use of irrigation waters. USDA Circular No. 969. Washington (DC): United States Department of Agriculture; 1955.
5. Richards LA. Diagnosis and improvement of saline and alkali soils. USDA Agriculture Handbook No. 60. Washington (DC): United States Department of Agriculture; 1954.
6. Freeze RA, Cherry JA. Groundwater. Englewood Cliffs (NJ): Prentice Hall; 1979.
7. Maina CW, Raude JM, Karanja FK, *et al*. Physicochemical and bacteriological assessment of groundwater quality in Laikipia Plateau, Kenya. *J Environ Sci Technol*. 2016;9(2):125-139.
8. Oduor SO, Schagerl M. Phytoplankton species diversity, abundance, and nutrient status of three Rift Valley saline-alkaline lakes of Kenya. *J Plankton Res*. 2007;29(12):1041-1053.
9. Todd DK, Mays LW. Groundwater hydrology. 3rd ed. New York: Wiley; 2005.
10. Piper AM. A graphic procedure in the geochemical interpretation of water analyses. *Trans Am Geophys Union*. 1944;25:914-923.
11. Gibbs RJ. Mechanisms controlling world water chemistry. *Science*. 1970;170(3962):1088-1090.
12. Kelly WP. Use of saline irrigation water. *Soil Sci*. 1963;95(4):355-391.
13. Eaton FM. Significance of carbonates in irrigation waters. *Soil Sci*. 1950;69(2):123-133.
14. Doneen LD. Notes on water quality in agriculture. Water Science and Engineering Paper No. 4001. Davis (CA): Department of Water Science and Engineering, University of California; 1964.
15. Sawyer CN, McCarty PL. Chemistry for sanitary engineers. 2nd ed. New York: McGraw-Hill; 1967.
16. Sisodia R, Moundiotiya C. Assessment of the water quality index of wetland Kalakho Lake, Rajasthan, India. *J Environ Hydrol*. 2006;14:1-11.
17. Chidambaram S, Anandhan P, Prasanna MV, *et al*. Hydrogeochemical characterisation of groundwater in Neyveli Basin, Cuddalore District, Tamil Nadu, South India. *Arab J Geosci*. 2012;5(1):151-163.
18. Karanth KR. Ground water assessment: development and management. New Delhi: Tata McGraw-Hill; 1987.