

Seasonal Groundwater Quality, WAWQI Weighting Sensitivity and Untreated-Use

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Abstract

Conventional water-quality indices can obscure decisive threshold failures when weighting gives disproportionate influence to a small number of parameters. This study quantified seasonal groundwater change and tested the robustness of an eight-parameter weighted arithmetic water-quality index (WAWQI) in Lamurde Area, Jalingo, Nigeria. Thirty fixed groundwater sources (24 hand-dug wells and six boreholes) were monitored during July-September 2025 and November 2025-January 2026, with three monthly observations aggregated to one seasonal value per source. The WAWQI incorporated pH, turbidity, total dissolved solids, electrical conductivity, nitrate, iron, zinc and total chromium; nitrate, total chromium and *Escherichia coli* were also retained as independent untreated-use warnings. Mean groundwater quality index (GWQI) decreased from 69.79 ± 46.66 to 45.00 ± 24.34 (Wilcoxon $W = 127$, $p = 0.029$), suggesting a more favourable composite wet-season condition. However, nitrate increased from 24.79 ± 4.79 to 82.14 ± 12.16 mg/L, all 30 wet-season sources exceeded 50 mg/L, and *Escherichia coli* remained detectable at every source in both seasons. Reciprocal weighting assigned 83.308% of formal weight to total chromium, 13.885% to iron and only 0.083% to nitrate. Equal weighting reversed the seasonal direction of the mean index (58.39 dry; 78.59 wet), nitrate exclusion changed no source class, and chromium exclusion changed most classes. The WAWQI was mathematically consistent but strongly model-dependent; decisive chemical and microbiological warnings should therefore remain non-compensatory.

1. Introduction

Groundwater is an important component of domestic water supply in rapidly urbanising cities, particularly where expansion of centralised potable-water infrastructure does not keep pace with population growth and changing water demand. Shallow hand-dug wells and boreholes can be vulnerable to recharge, urban drainage, onsite sanitation, waste disposal and other near-surface contaminant sources. In tropical environments, pronounced wet and dry seasons can modify groundwater levels, solute mobilisation, dilution and contaminant transport, producing water-quality responses that differ among parameters.

Seasonal hydrology can alter groundwater quality in several directions simultaneously. Recharge may dilute some dissolved constituents while mobilising nutrients, faecal contaminants and solutes accumulated in soils and the unsaturated zone. High-frequency monitoring in suburban Dakar showed that heavy rainfall can drive episodic recharge and rapid nitrate flushing from sanitation-affected vadose-zone material into shallow groundwater (Pouye et al. 2023). Microbiological responses may also be seasonally complex: groundwater self-supply studies in urban Indonesia and peri-urban Nigeria have reported persistent faecal contamination and, in some settings, greater *Escherichia coli* contamination during wetter conditions (Genter et al. 2023; Rabiou et al. 2022; Putri et al. 2025).

Groundwater assessment commonly generates many physicochemical and microbiological measurements that are difficult to communicate simultaneously. Water Quality Indices (WQIs) simplify

this information by transforming selected variables into a single dimensionless score. A typical WQI involves parameter selection, transformation to sub-indices or quality ratings, assignment of weights and aggregation to a final index. Their ease of interpretation has led to widespread application in groundwater and surface-water assessment (Manna and Biswas 2023).

The simplification achieved by a composite index also introduces model dependence. WQI outputs are affected by parameter selection, sub-index formulation, weighting and aggregation. Uddin et al. (2023) quantified uncertainty across these stages, while Ding et al. (2023) explored alternative weighting and aggregation structures to improve WQI performance. Moeinzadeh et al. (2024) further identified parameter choice and the eclipsing problem as continuing methodological concerns. Eclipsing occurs when unacceptable behaviour in one parameter is obscured by more favourable values in others, leading the aggregate score to appear better than the parameter-specific evidence suggests.

This issue is particularly relevant to reciprocal weighting, in which parameter weight increases as the numerical value of its adopted standard decreases. A constituent with a low permissible concentration can therefore dominate the final index, while a health-relevant parameter with a larger numerical guideline value can contribute little to the arithmetic score. The resulting WQI may remain useful for relative physicochemical comparison, but it should not automatically be interpreted as equivalent to drinking-water safety.

The distinction is critical for nitrate and microbiological contamination. Nitrate in shallow groundwater can respond rapidly to recharge and anthropogenic nitrogen loading, while *E. coli* is an indicator of faecal contamination whose detection cannot logically be offset by favourable chemical measurements. Recent integrated groundwater studies have increasingly separated general index-based suitability from contaminant-specific risk or microbiological evidence (Naz et al. 2024; Yan et al. 2024).

The study was undertaken in Lamurde Area, Jalingo, Taraba State, Nigeria, where domestic water supply includes shallow hand-dug wells and boreholes. The analytical network comprised 30 fixed groundwater sources – 24 hand-dug wells and six boreholes - monitored at the same locations during July-September 2025 and November 2025-January 2026. Three monthly observations contributed to each seasonal value.

The groundwater results presented an interpretive contradiction. Mean GWQI decreased from 69.79 in the dry season to 45.00 in the wet season, suggesting a more favourable composite condition, yet all 30 sources exceeded 50 mg/L nitrate during the wet season and *Escherichia coli* remained detectable throughout the network in both seasons. The reciprocal weighting structure simultaneously assigned 83.308% of the formal weight to total chromium and 13.885% to iron, but only 0.083% to nitrate.

This paper therefore evaluates whether the seasonal groundwater interpretation is robust to the WAWQI weighting architecture. The objectives were to: (i) characterise paired seasonal groundwater conditions; (ii) calculate dry- and wet-season GWQI using the adopted eight-parameter WAWQI; (iii) compare the composite classifications with independent nitrate, total-chromium and *Escherichia coli* warning states;

and (iv) test classification sensitivity under equal weighting, nitrate exclusion and total-chromium exclusion. The central proposition is that an apparently favourable WAWQI can coexist with poorer untreated-use status when strongly weighted parameters improve while decisive health-related variables deteriorate.

2. Materials and Methods

2.1 Study area and monitoring network

The study area is Lamurde, Jalingo, Taraba State, Nigeria, within an approximately 3.885 km² analytical boundary. Residential development, shallow groundwater abstraction and urban drainage occur within the domain. Spatial data were referenced to WGS 84 / UTM Zone 32N (EPSG:32632).

2.2 Sampling framework and seasonal design

Site selection was informed by a broader reconnaissance network, but all inferential analyses in this article were restricted to 30 fixed groundwater sources, G1-G30: 24 hand-dug wells and six boreholes. The same sources were retained across seasons to permit paired source-level comparison.

Wet-season monitoring comprised July, August and September 2025, and dry-season monitoring comprised November and December 2025 and January 2026. Each location therefore contributed three monthly observations per season. Monthly observations were aggregated to one seasonal value per source for the principal paired inference, giving 30 paired seasonal observations. The monitoring location, not the individual monthly measurement, was the primary inferential unit.

2.3 Water-quality variables and laboratory scope

The groundwater dataset comprised pH, turbidity, total dissolved solids (TDS), electrical conductivity (EC), nitrate, iron, zinc, total chromium, dissolved oxygen (DO), five-day biochemical oxygen demand (BOD5) and *Escherichia coli*. The WAWQI used eight physicochemical variables: pH, turbidity, TDS, EC, nitrate, iron, zinc and total chromium. DO and BOD5 were interpreted separately as supporting indicators, and *Escherichia coli* was retained as an independent microbiological warning. Lead did not enter the final analytical framework.

Groundwater samples were collected in pre-cleaned containers appropriate to the intended analyses, labelled by source and sampling period, kept cooled at approximately 4 degrees C and transported for laboratory processing. Microbiological samples were handled aseptically. Total chromium was measured after alkaline hypobromite oxidation using ChromaVer 3 Chromium Reagent and was interpreted as laboratory-reported total chromium against the adopted 0.05 mg/L criterion.

2.4 Standards and WAWQI weighting

Reference values used for both parameter screening and WAWQI calculation were fixed before statistical interpretation. World Health Organization (2026) provided the international drinking-water framework where applicable, while the Nigerian Standard for Drinking Water Quality (NIS 554:2015) supplied the national comparison values retained in the study (Standards Organisation of Nigeria 2015). Table 1 reports the standards, ideal values and reciprocal unit weights used in the eight-parameter groundwater index.

Table 1
Standards, ideal values and unit weights used in the eight-parameter groundwater WAWQI.

Parameter	Unit	Standard Sn	Ideal V0	Unit weight Wn	Normalised weight (%)
pH	pH unit	8.5	7.0	0.004900	0.490
Turbidity	NTU	5.0	0	0.008331	0.833
TDS	mg/L	500	0	0.000083	0.008
EC	microS/cm	1,000	0	0.000042	0.004
Nitrate	mg/L as NO3-	50	0	0.000833	0.083
Iron	mg/L	0.30	0	0.138847	13.885
Zinc	mg/L	3.0	0	0.013885	1.388
Total chromium	mg/L	0.05	0	0.833079	83.308

2.5 Weighted Arithmetic Water Quality Index

For each source-season observation, WAWQI was computed using the arithmetic framework of Brown et al. (1972). Parameter n was first converted to a quality rating using its measured value, adopted standard and ideal value:

$$q_n = 100 \frac{V_n - V_0}{S_n - V_0}$$

1

where q_n is the parameter quality rating, V_n is the observed value, S_n is the adopted standard and V_0 is the ideal value. V_0 was 7.0 for pH and zero for the remaining parameters. Reciprocal unit weights were then assigned as:

$$W_n = \frac{K}{S_n}$$

2

where K is the normalising constant; K = 0.041654 for the adopted eight-parameter set. The weighted sub-index and final groundwater index were obtained from:

3

$$SI_n = W_n q_n$$

4

$$GWQI = \sum SI_n$$

Table 2
Groundwater WQI
classification used in the
study.

GWQI	Classification
0–25	Excellent
26–50	Good
51–75	Fair
76–100	Poor
> 100	Unsuitable

The categorical terms refer to composite physicochemical condition under the specified WAWQI model and were not treated as stand-alone declarations of potability.

2.6 Independent warning classification

The composite GWQI classification was separated from three binary untreated-use warning states: detectable Escherichia coli in 100 mL, nitrate > 50 mg/L and total chromium > 0.05 mg/L. These warnings were non-compensatory: a favourable GWQI category did not override a parameter-specific warning. Turbidity remained an operational treatment-performance variable and BOD5 an indicator of biodegradable organic loading and treatment demand.

2.7 Sensitivity analysis

The principal reciprocal-weight WAWQI was evaluated against three transparent sensitivity scenarios. First, all eight parameters were assigned equal weight (1/8 each). Second, nitrate was removed and the index recalculated. Third, total chromium was removed and the index recalculated. The analysis was diagnostic: it tested whether source classification and the direction of seasonal interpretation were robust to the weighting architecture; it did not propose a replacement WQI.

For each scenario, site-level class retention was calculated as the number of G1-G30 sources retaining the original reciprocal-WAWQI class divided by 30 and expressed as a percentage.

2.8 Statistical analysis

Seasonal inference used the paired source-level means for G1-G30. Descriptive statistics included mean, standard deviation, range and criterion-conformity frequency. The Shapiro-Wilk test was applied to wet-minus-dry paired differences. Approximately normal differences were analysed with paired-samples t-tests and paired Cohen's d_z ; non-normal differences were analysed with Wilcoxon signed-rank tests, with Hodges-Lehmann paired shift and matched-pairs rank-biserial effect reported where applicable. Benjamini-Hochberg false-discovery-rate adjustment was applied to the predefined family of 11 groundwater seasonal comparisons. Criterion exceedance and statistical significance were interpreted as separate evidence.

2.9 Data integrity and reproducibility

Data checks addressed duplicate records, missing values, identifier consistency, units and transcription errors before seasonal aggregation. Unusual observations were retained unless a source-record error was identified. The analytical sequence was source-month observations, seasonal source means, standards comparison, WAWQI and class assignment, independent warning flags, paired seasonal inference, multiplicity adjustment and prespecified sensitivity scenarios.

3. Results

3.1 Seasonal groundwater behaviour

Groundwater quality changed substantially between seasons, but the direction of change differed among parameters. After Benjamini-Hochberg adjustment, statistically supported changes remained for pH, turbidity, nitrate, zinc, total chromium and *E. coli*. TDS, EC, iron and DO did not show statistically consistent network-wide seasonal change, while BOD5 recorded $p = 0.035$ but did not remain significant after false-discovery-rate correction ($q = 0.054$).

Table 3
Consolidated seasonal comparison of groundwater-quality indicators across G1-G30.

Indicator	Dry mean $\pm$ SD	Wet mean $\pm$ SD	Test	BH q	Principal result
pH	6.853 $\pm$ 0.276	6.590 $\pm$ 0.332	t(29)=-8.845	< 0.001	Significant decline
Turbidity (NTU)	2.402 $\pm$ 1.443	8.400 $\pm$ 9.601	W = 30	< 0.001	Significant increase
TDS (mg/L)	554.419 $\pm$ 161.168	589.878 $\pm$ 219.330	t(29) = 0.758	0.455	No consistent change
EC (microS/cm)	889.671 $\pm$ 302.262	983.639 $\pm$ 325.515	W = 146	0.105	No significant change
Nitrate (mg/L)	24.788 $\pm$ 4.793	82.145 $\pm$ 12.157	W = 0	< 0.001	30/30 wet exceedances
Iron (mg/L)	0.255 $\pm$ 0.279	0.163 $\pm$ 0.096	W = 167	0.196	Lower mean; heterogeneous
Zinc (mg/L)	0.772 $\pm$ 0.356	0.306 $\pm$ 0.176	W = 0	< 0.001	Uniform decline
Total Cr (mg/L)	0.034 $\pm$ 0.021	0.022 $\pm$ 0.014	W = 72	0.027	Significant decline
DO (mg/L)	7.030 $\pm$ 0.417	7.263 $\pm$ 0.516	t(29) = 1.773	0.106	No significant shift
BOD5 (mg/L)	7.631 $\pm$ 3.287	9.410 $\pm$ 2.590	W = 130	0.054	Not retained after FDR
E. coli (CFU/100 mL)	18.997 $\pm$ 7.665	24.778 $\pm$ 9.844	W = 67	< 0.001	Universal microbiological failure

3.2 Nitrate and microbiological restrictions

Nitrate exhibited the strongest uniform adverse chemical response. Mean nitrate increased from 24.79 $\pm$ 4.79 mg/L in the dry season to 82.14 $\pm$ 12.16 mg/L in the wet season. All 30 sources recorded higher wet-season concentrations and every source shifted from $\leq$ 50 mg/L in the dry season to $>$ 50 mg/L in the wet season. The Wilcoxon test produced W = 0 and q < 0.001, with a Hodges-Lehmann paired increase of 57.50 mg/L and a maximal rank-biserial effect of 1.000.

Microbiological contamination was persistent. *E. coli* was detected at every groundwater location in both seasons and all 180 source-month observations were positive. Mean counts increased from 19.00 $\pm$ 7.67 to 24.78 $\pm$ 9.84 CFU/100 mL; 23 of 30 sources recorded higher wet-season values. The seasonal increase was significant (W = 67, q < 0.001).

3.3 Other seasonal changes

Mean pH declined from 6.85 to 6.59 and the number of sources within the adopted 6.5–8.5 range fell from 27 to 14. Mean turbidity increased from 2.40 to 8.40 NTU and criterion conformity declined from 90.0% to 56.7%. Mean iron declined from 0.255 to 0.163 mg/L, with conformity improving from 73.3% to 93.3%, although the network-wide seasonal change was not significant after adjustment. Zinc declined significantly at all 30 sources and remained below 3.0 mg/L throughout. Total chromium declined from 0.034 to 0.022 mg/L and conformity with the 0.05 mg/L criterion improved from 24/30 to 29/30 sources.

3.4 Seasonal GWQI and class movement

Despite the adverse nitrate and microbiological response, mean GWQI decreased significantly from 69.79 ± 46.66 during the dry season to 45.00 ± 24.34 during the wet season. Paired differences were non-normal (Shapiro-Wilk $W = 0.877$, $p = 0.002$), and the Wilcoxon test identified a significant reduction ($W = 127$, $p = 0.029$). The Hodges-Lehmann paired shift was -15.30 GWQI units with a bootstrap 95% confidence interval of -40.38 to -0.93 .

Table 4
Seasonal groundwater WQI summary and class distribution.

Source: Research data (2026)

Season	Mean $\pm$ SD	Range	Excellent	Good	Fair	Poor	Unsuitable
Dry	69.79 ± 46.66	10.38-179.88	2 (6.7%)	10 (33.3%)	9 (30.0%)	3 (10.0%)	6 (20.0%)
Wet	45.00 ± 24.34	10.04-120.56	7 (23.3%)	15 (50.0%)	5 (16.7%)	2 (6.7%)	1 (3.3%)

Eighteen sources recorded lower wet-season GWQI values, 12 increased, 15 moved to a more favourable class, 11 retained their class and four moved to a less favourable class. Source-level variation was pronounced: G3 shifted from 166.21 (Unsuitable) to 33.94 (Good), while G5 shifted from 10.38 (Excellent) to 120.56 (Unsuitable).

3.5 Weight dominance and WQI-warning discordance

The reciprocal weighting structure was strongly unequal. Total chromium contributed 83.308% of the normalised weight and iron 13.885%; together they represented 97.193% of the formal weighting structure. Nitrate contributed only 0.083%. At the observed seasonal means, chromium and iron together contributed approximately 98.9% of the dry-season GWQI and 96.5% of the wet-season GWQI.

During the dry season, no nitrate warnings occurred, six sources exceeded the total-chromium criterion and all 30 sources carried an *E. coli* warning. During the wet season, all 30 sources carried a nitrate warning, one exceeded the chromium criterion and all 30 remained *E. coli* positive. Thus, 22 wet-season sources were classified Excellent or Good by WAWQI while all 30 simultaneously failed both the nitrate and microbiological untreated-use criteria.

3.6 Sensitivity of WAWQI classification

Sensitivity analysis confirmed strong dependence of the composite classification on the weighting architecture. Removing nitrate changed no groundwater class in either season. Equal weighting produced mean index values of 58.39 in the dry season and 78.59 in the wet season, reversing the direction of the seasonal conclusion; only 11/30 dry-season and 2/30 wet-season sources retained their original class. Excluding total chromium retained the original class at only 13/30 dry-season and 8/30 wet-season sources.

4. Discussion

4.1 Parameter-specific seasonality in shallow urban groundwater

The Lamurde groundwater response was multidirectional: nitrate, turbidity and *E. coli* deteriorated while zinc and total chromium improved, and several mineralisation indicators showed no consistent network-wide change. This pattern demonstrates why hydrological season should not be reduced to a simple dilution-versus-concentration narrative. Recharge can alter residence time, mobilise solutes from the unsaturated zone, increase surface or wellhead ingress and simultaneously dilute some dissolved constituents. The observed results therefore support parameter-specific seasonal interpretation.

The nitrate response was particularly strong. Pouye et al. (2023) demonstrated through high-frequency monitoring and vadose-zone modelling in Dakar that intense rainfall can rapidly mobilise nitrate from sanitation-affected unsaturated-zone material to shallow groundwater. The Lamurde study did not perform isotope or source-tracer analysis and therefore cannot assign the universal wet-season nitrate increase to a unique source. It nevertheless shows a network-wide seasonal nitrogen response that is directly relevant to drinking-water management.

4.2 Persistent faecal contamination and seasonal vulnerability

The universal detection of *E. coli* in both seasons means that microbiological non-compliance was more persistent than any single chemical warning. This finding is consistent with evidence from groundwater self-supply systems where wet-season contamination can increase but dry-season contamination also remains substantial. Genter et al. (2023) found complex seasonal patterns in urban Indonesian self-supply sources, while Putri et al. (2025) documented a rainy-season *E. coli* flush and showed that rainfall and source-pathway geometry altered contamination odds. In peri-urban Ibadan, Rabiou et al. (2022) also reported significantly greater *E. coli* recovery from wells during the wet season. These comparisons support the plausibility of rainfall-enhanced microbial vulnerability while reinforcing that the Lamurde data establish contamination, not a unique faecal source.

4.3 Why GWQI improved while untreated-use safety deteriorated

The principal scientific finding is the divergence between the composite GWQI and the parameters independently controlling untreated-use restrictions. Mean GWQI improved from 69.79 to 45.00 and the number of Unsuitable sources fell from six to one, yet all 30 sources exceeded the nitrate criterion in the wet season and all remained microbiologically non-compliant. The apparent contradiction is explained by the WAWQI arithmetic: total chromium and iron together represented 97.193% of the normalised reciprocal weight, whereas nitrate contributed only 0.083%.

Because the index weight is inversely related to the numerical standard, a small-standard parameter can exert much greater influence on the composite score than a parameter with a larger numerical guideline value. The wet-season reduction in total chromium, coupled with the lower iron mean, consequently pulled the index downward much more strongly than the substantial nitrate increase pushed it upward. The calculation is internally consistent, but its public-health interpretation is conditional on recognising the weighting structure.

4.4 WQI uncertainty, parameter choice and eclipsing

The Lamurde result is consistent with broader methodological concern about WQI model dependence. Uddin et al. (2023) showed that WQI reliability can be affected by parameter selection, sub-index functions, weighting and aggregation. Ding et al. (2023) developed alternative combined weights and aggregation functions to reduce WQI uncertainty. Moeinzadeh et al. (2024), in a critical review in *Water Research*, identified the eclipsing problem as a major motivation for refining WQI parameter sets. Manna and Biswas (2023) similarly emphasised that WQI models differ in parameter selection, weighting and aggregation and that model accuracy must be considered when converting multidimensional drinking-water data to a single score.

The present study adds a practical groundwater example in which the direction of the seasonal conclusion changed under a simple alternative weighting assumption. Reciprocal weighting suggested improvement (69.79 to 45.00), whereas equal weighting suggested deterioration (58.39 to 78.59). This does not establish equal weighting as superior. It demonstrates that the qualitative interpretation is model-dependent and should be accompanied by sensitivity analysis.

4.5 Nitrate exclusion versus chromium exclusion

The exclusion scenarios provide direct evidence of unequal arithmetic influence. Removing nitrate changed no groundwater class, even though nitrate increased at every source and exceeded 50 mg/L throughout the wet-season network. Removing total chromium, by contrast, changed most source classes. This does not diminish the importance of chromium; its low reference concentration legitimately reflects a stringent standard. The result shows that health significance and arithmetic influence within a composite index are not equivalent constructs.

Recent integrated groundwater assessments also demonstrate the value of retaining contaminant-specific information outside a general index. Yan et al. (2024), for example, combined an entropy-weighted groundwater index with a separate nitrate health-risk analysis. Naz et al. (2024) combined WQI and geostatistics while identifying microbiological contamination as a distinct management challenge. These approaches support a layered interpretation in which WQI provides synthesis but does not replace contaminant-specific evaluation.

4.6 Non-compensatory interpretation for drinking-water assessment

The Lamurde findings support a clear distinction: WAWQI answers a question about relative composite physicochemical condition under a specified mathematical architecture, whereas parameter-specific standards answer whether a constituent independently restricts untreated use. These questions are complementary but not interchangeable. A source classified as Excellent or Good by WAWQI may still be unacceptable for untreated drinking if *E. coli* is detected or nitrate exceeds the applicable criterion.

For this reason, the study retained *E. coli*, nitrate and total chromium as non-compensatory warnings. The rule can be expressed simply: favourable GWQI does not imply absence of warning. This interpretive safeguard is especially important when WQI classes are communicated to non-specialist users, because labels such as Excellent and Good can otherwise be mistaken for direct statements of potability.

4.7 Engineering and monitoring implications

The results have direct water-supply implications. First, monitoring programmes should include wet-season sampling; a dry-season-only programme would have missed the universal nitrate exceedance observed in Lamurde. Second, treatment decisions must be contaminant-specific. Microbial contamination requires effective source protection and disinfection, while nitrate requires processes capable of nitrate removal or an alternative source; chlorination alone does not resolve nitrate contamination. Third, elevated wet-season turbidity can complicate microbial treatment and should be considered where disinfection is applied.

WQI reports used by regulators or communities should therefore present both the composite class and the independent warning status. A visually favourable or statistically improved WQI should not be allowed to obscure a decisive chemical or microbiological restriction.

4.8 Methodological contribution and limitations

The paper does not propose a new WQI. Its methodological contribution is a reproducible audit of an established arithmetic index through three safeguards: transparent disclosure of parameter weights, prespecified sensitivity analysis and independent retention of decisive warning variables. This approach can be applied to conventional WQI studies without replacing the underlying index.

Several limitations define the scope of inference. The study covers 30 groundwater sources within one approximately 3.885 km² urban domain and one wet and one dry monitoring period; it does not establish

interannual trends or conditions across all of Jalingo or Taraba State. Nitrate and *Escherichia coli* source attribution was not established and would require source-specific tracers, isotopes or microbial source tracking. The sensitivity analysis tested three transparent alternatives but did not exhaust all possible WQI formulations. Instrument-specific detection limits and complete laboratory control metadata were not available in the manuscript source records and are therefore not asserted here.

5. Conclusion and Recommendations

5.1 Conclusion

Groundwater quality in Lamurde changed substantially and non-uniformly between the sampled seasons. The mean WAWQI improved from 69.79 in the dry season to 45.00 in the wet season, but this apparent composite improvement did not correspond to improved untreated-use safety. Nitrate increased from 24.79 to 82.14 mg/L and exceeded 50 mg/L at all 30 wet-season sources, while *E. coli* remained detectable throughout both seasons. Turbidity also increased and pH declined significantly.

The discordance was structurally linked to reciprocal weighting. Total chromium and iron accounted for 97.193% of the formal weight, while nitrate contributed only 0.083%. Removing nitrate changed no groundwater class, chromium exclusion altered most classes, and equal weighting substantially changed site classifications and reversed the direction of the seasonal mean. The WAWQI result is reported as relative composite physicochemical condition, which does not in itself confirm drinking-water safety.

The broader methodological conclusion is that conventional WQI applications has to disclose parameter weights, test sensitivity where a small number of variables dominate the composite score, and retain decisive chemical and microbiological thresholds independently. Composite condition and untreated-use warnings provide complementary evidence and did not compensate for one another.

5.2 Recommendations

- Groundwater monitoring programmes using WAWQI should report the underlying parameter weights and include sensitivity analysis where one or two variables dominate the composite score.
- Nitrate, microbiological indicators and other decisive threshold exceedances should remain visible independently of WQI classification.
- Lamurde monitoring should retain wet-season coverage because dry-season sampling alone would not have detected the universal wet-season nitrate exceedance observed in this study.
- Source-level treatment assessment should be contaminant-specific: microbial control and nitrate removal require different management and treatment responses.
- Repeated monitoring over additional hydrological years is required to determine whether the 2025–2026 seasonal pattern is recurrent.

- Future source-attribution work should consider nitrate isotopes, microbial source tracking, source-specific chemical tracers and higher-resolution hydrogeological evidence.

Declarations

Declaration on Generative AI and AI-Assisted Technologies

During manuscript preparation, generative AI tools were used for language refinement, manuscript organisation and editorial support. The scientific analyses, interpretation, source verification and final content remain the responsibility of the authors.

Author Contribution

Engr. E. M. Kungwa led the conceptualisation, methodology, investigation, data curation, formal analysis, validation, visualisation and preparation of the original draft. Professor A. A. Adegbola and Professor O. S. Olaniyan contributed supervision, methodology, validation, review and editing.

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Data Availability

Some of the data supporting the findings of this study are presented in the manuscript. The source coded G1–G30 analytical dataset, monthly-to-seasonal aggregation table, WAWQI calculation matrix, source level warning classifications and outputs from the three sensitivity analyses are retained by the authors and are available from the corresponding author on reasonable request, subject to the journal's data sharing policy

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Figures

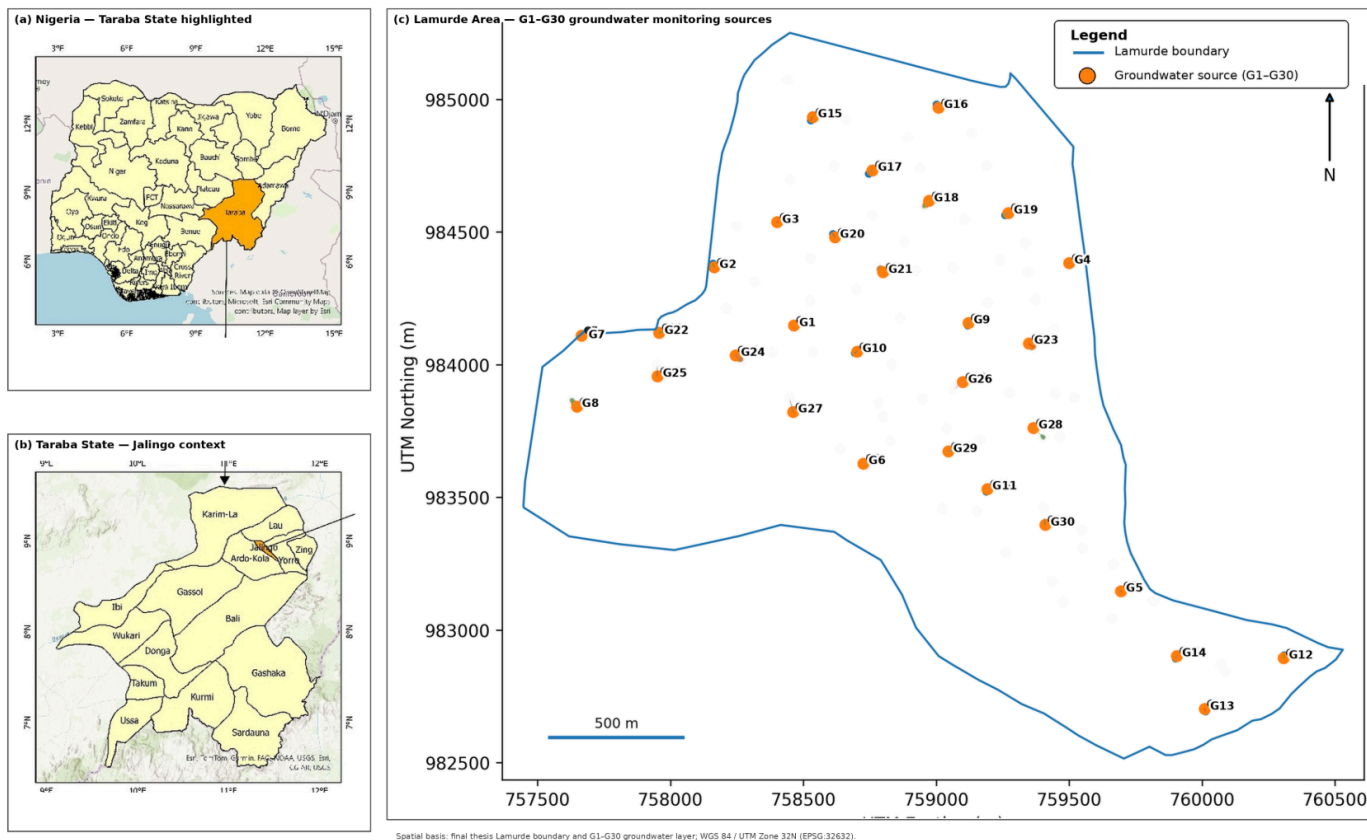


Figure 1

Location of the study area and distribution of G1-G30 groundwater monitoring sources in Lamurde Area, Jalingo, Taraba State, Nigeria.

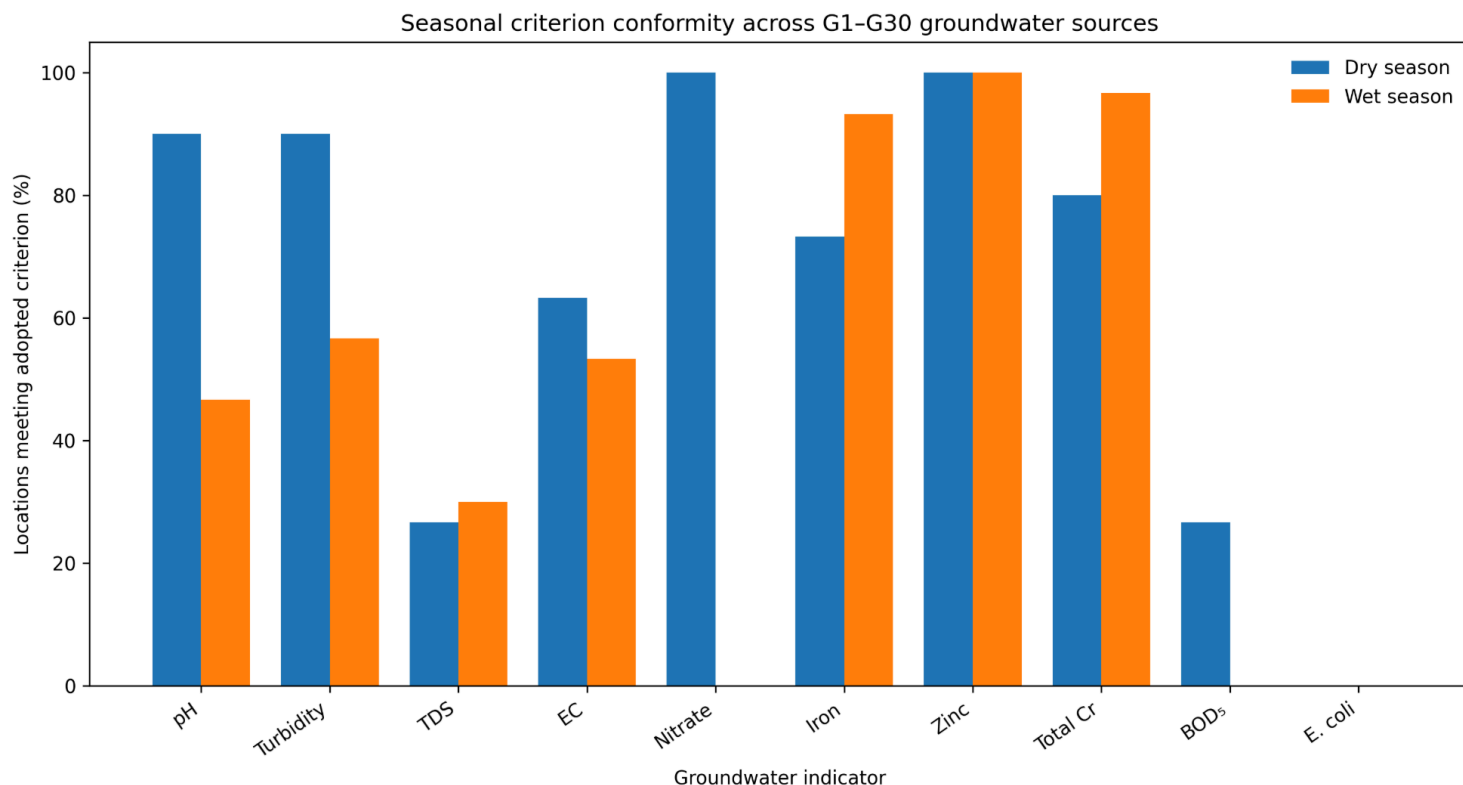


Figure 2

Seasonal conformity of G1-G30 groundwater sources with the adopted physicochemical, operational and microbiological criteria. DO is excluded because no binary conformity criterion was applied.

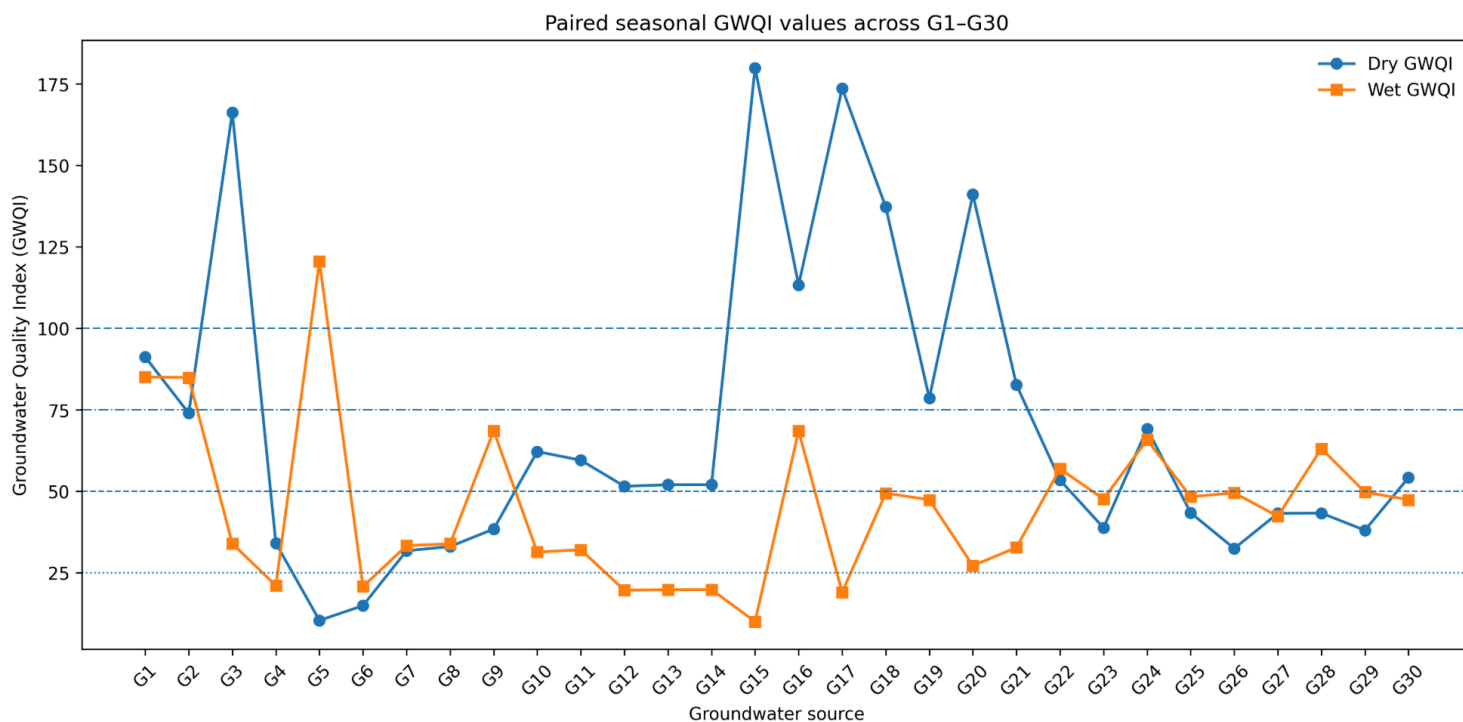


Figure 3

Paired dry- and wet-season groundwater quality index values for G1-G30. Horizontal reference lines represent WAWQI class boundaries at 25, 50, 75 and 100.

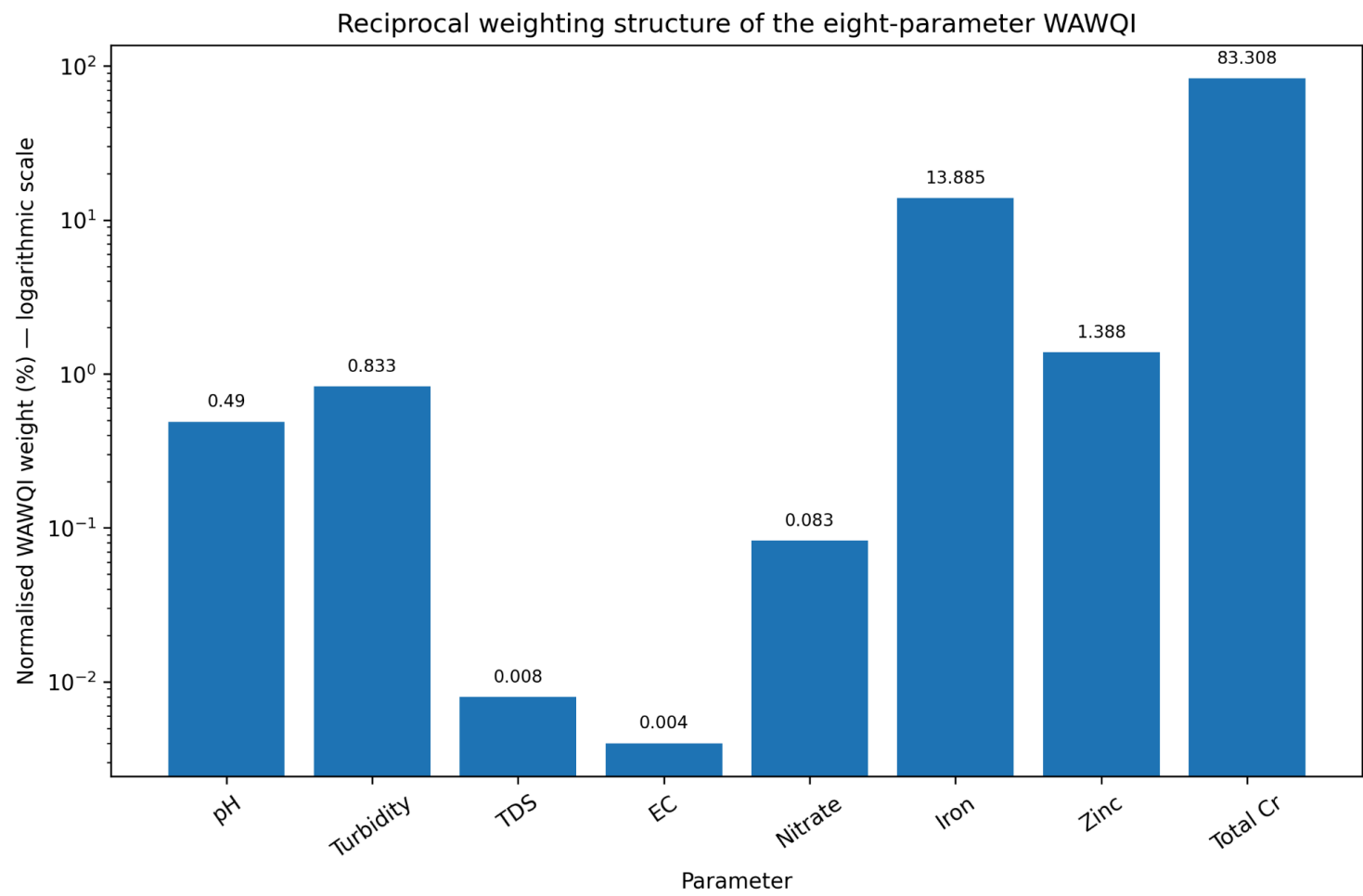


Figure 4

Normalised reciprocal weights of the eight parameters used in the groundwater WAWQI. The vertical axis is logarithmic to display the large differences in parameter weight.

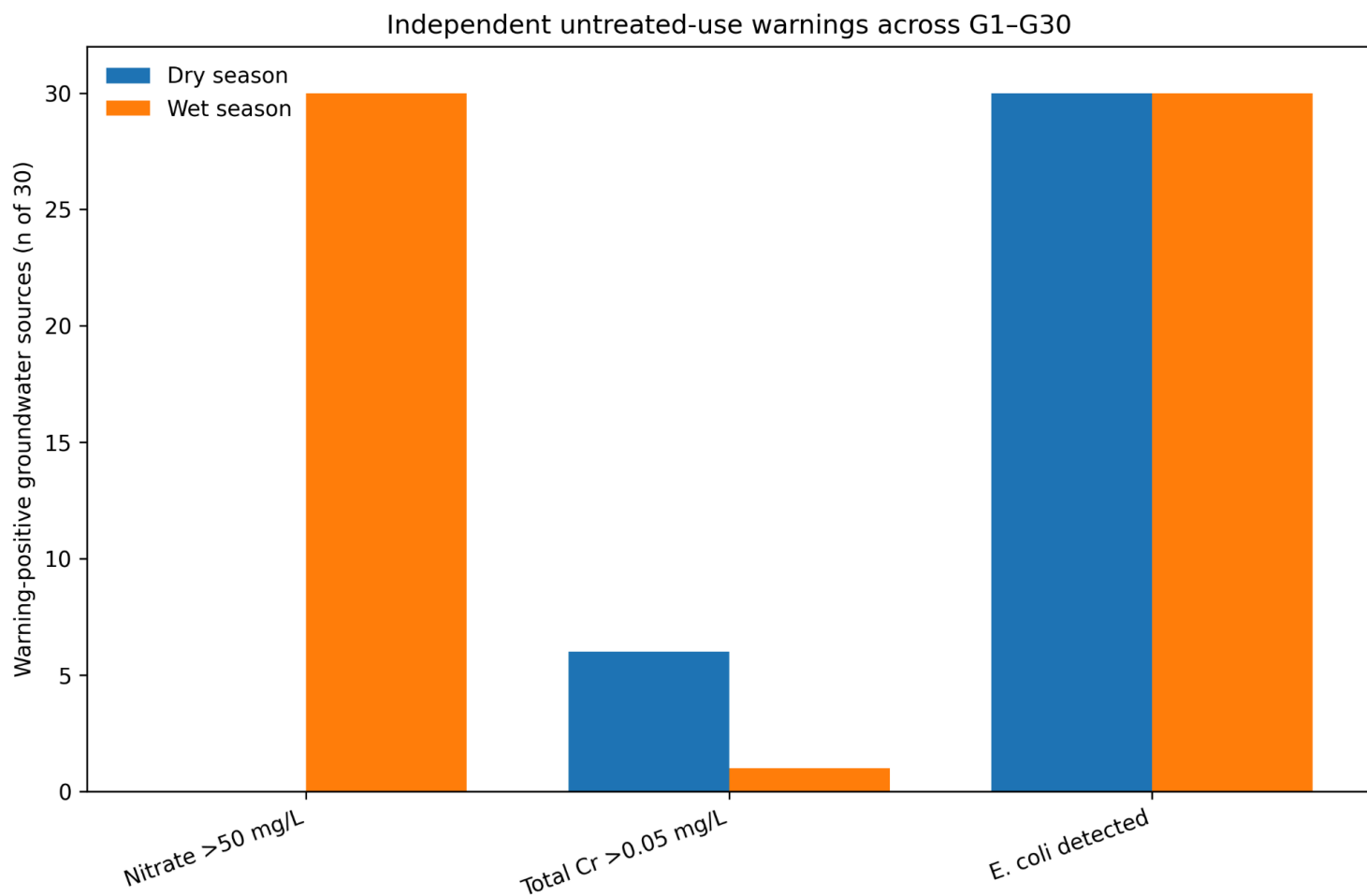


Figure 5

Number of G1-G30 groundwater sources with independent nitrate, total-chromium and E. coli untreated-use warnings during the dry and wet seasons.

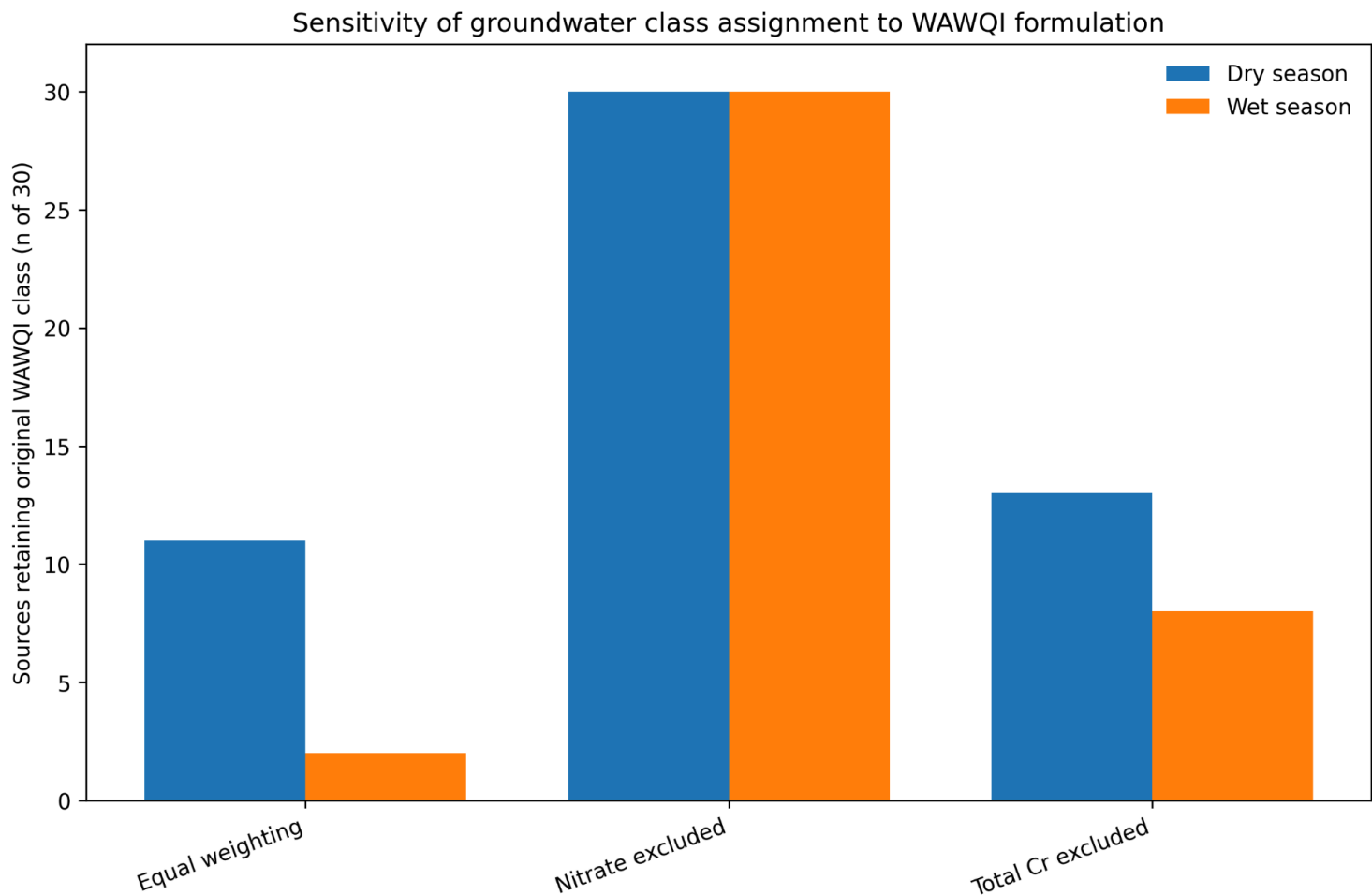


Figure 6

Number of groundwater sources retaining their original reciprocal-WAWQI class after equal weighting, nitrate exclusion and total-chromium exclusion. Maximum retention is 30 sources per season.