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Probabilistic health-risk assessment of nitrate in Continental Intercalaire groundwater (Adrar–Timimoun oases, Algerian Sahara): a Monte Carlo simulation and sensitivity analysis

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Abstract

A hazard quotient derived from a singular site and a specific set of exposure parameters indicates if the typical individual is at danger, although it does not assess the probability of such risk when considering the natural dispersion of nitrate and human water consumption. We consequently reevaluate the non-carcinogenic hazard of nitrate in the Continental Intercalaire aquifer of the Adrar–Timimoun oasis (Algerian Sahara) using probabilistic methods. From 25 samples (nitrate 8.6 - 100 mg L^{-1}, mean 44.3), we conducted 10,000 Monte Carlo iterations to simulate the hazard quotient across five age demographics, resampling nitrate concentrations from the empirical data while deriving ingestion rates and body weights from age-specific distributions; subsequently, a Spearman-based sensitivity analysis ranked the risk determinants. The simulated hazard quotient is strongly right-skewed, its median falling from 2.48 in infants to 0.76 in adults. The probability that it exceeds one is 77 % for infants and declines to 61, 55, 38 and 33 % for young children, children, teenagers and adults, so that for a random infant and a random location the risk is more likely than not. The sensitivity analysis is unambiguous: the nitrate concentration governs the outcome (Spearman $\rho \approx 0.91$), far ahead of the ingestion rate (0.29) and body weight (-0.21). The probabilistic view sharpens the deterministic diagnosis, flags infants as the group to protect first, and shows that lowering nitrate, rather than refining exposure assumptions, is where mitigation should focus.

Keywords: Monte Carlo simulation, Nitrate, Probabilistic health risk, Hazard quotient, Sensitivity analysis, Continental Intercalaire, Algerian Sahara

1. Introduction

Few contaminants illustrate the double face of groundwater as sharply as nitrate. It is colourless and tasteless, highly soluble, weakly retained by most aquifer materials, and, once it has reached an aquifer, awkward and costly to remove (Ward et al., 2018). Nitrogen fertilizers, manure, septic systems, and the oxidation of nitrogenous waste are some of the sources of this substance, which are already well-known and difficult to eliminate (Serio et al., 2018; Su et al., 2013). Furthermore, the health significance of this condition is no longer limited to the traditional instance of methaemoglobinemia in infants (Fewtrell, 2004): epidemiological work now links long-term exposure, even below the regulatory limit, to colorectal cancer and other outcomes (Schullehner et al., 2018; Ward et al., 2018), which is precisely why the World Health Organization retains a guideline value of 50 mg L^{-1} as NO_3^- (WHO 2017, 2022).

This tension is felt acutely in the Algerian Sahara. In the oases of Adrar and Timimoun the Continental Intercalaire aquifer is, quite literally, the only permanent water; its chemistry is dominated by the dissolution of evaporites and by evaporation along very long, slow flow paths (Benhamida, 2021; Darling et al., 2018; Edmunds et al., 2003; Hamed et al., 2023). Against this naturally saline background, recent studies have documented a rising, and clearly anthropogenic, nitrate load and the drinking-water and health concerns that come with it (Bouselsal et al., 2024; Lakhdari & Bouselsal, 2024). The same aquifer that makes life possible also delivers whatever nitrogen the surface sends down to it.

The health risk of nitrate is most often quantified with the deterministic hazard-quotient framework of the United States Environmental Protection Agency, in which a single exposure estimate is compared with a reference dose (Adimalla & Qian 2019; Amiri et al., 2023; He & Wu 2019; Li & Wu, 2019). The approach is transparent and widely used, but it hides two things that matter here. First, nitrate is not one number: it varies by more than an order of magnitude across the aquifer. Second, people are not one number either - how much water a person drinks, and how much they weigh, differ within every age group. Compressing all of this into point values yields a single hazard quotient but cannot say how probable an unacceptable exposure actually is, nor how sensitive that verdict is to the assumptions behind it (Burmaster & Anderson 1994; Rao, 2026).

Probabilistic risk assessment was designed for exactly this situation. By describing each uncertain input as a distribution and

propagating those distributions through the exposure model with Monte Carlo simulation, it returns the full distribution of the hazard quotient, the probability that the risk threshold is crossed, and - through a companion sensitivity analysis - a ranking of the inputs that drive the result (Burmaster & Anderson, 1994; Kentel & Aral, 2005; Saltelli et al., 2008; Sobol, 2001). The method is now common currency for nitrate in arid and semi-arid aquifers, from Iran to India and China (Hallal et al., 2026; Mohanta et al., 2026; Sakizadeh & Zhang, 2020; Zhang et al., 2018), yet it has not, to our knowledge, been applied to the Continental Intercalaire of the western Sahara. A companion deterministic study of the same wells had already classified most of the water as unfit for drinking and singled out nitrate as a leading concern, with an age-resolved hazard quotient above one in 72 % of samples for infants. Here we take that result one step further and ask a different question: given the variability we actually observe, how likely is an unacceptable nitrate risk for each age group, and what drives it? Concretely, the aims are (i) to build a Monte Carlo model of the nitrate hazard quotient for five age groups, (ii) to express the risk as a probability of exceeding the threshold, and (iii) to identify, by sensitivity analysis, the input that most controls the risk - so that mitigation can be aimed where it will count.

2 Materials and methods

2.1 Study area and data

The study draws on the same 25 groundwater samples of the Continental Intercalaire aquifer of the Adrar–Timimoun–Reggane area as the companion deterministic work. The aquifer, part of the North-Western Sahara Aquifer System, is hosted in Lower-Cretaceous continental sandstones under a hyper-arid climate; its groundwater is old, highly mineralised and recharged only slowly (Darling et al., 2018; Edmunds et al., 2003). In our samples nitrate ranges from 8.6 to 100 mg L^{-1} (mean 44.3), and 11 of the 25 exceed the WHO guideline of 50 mg L^{-1}. Rather than fit a theoretical law to these values, we use the measured set itself as the empirical distribution of the nitrate concentration in the simulation, so that the real, and strongly skewed, spatial variability of nitrate across the aquifer is carried into the risk calculation unaltered.

2.2 Hazard-quotient model

Non-carcinogenic risk from drinking-water ingestion is expressed by the hazard quotient, $HQ = (C \times IR) / (BW \times RfD)$, where C is the nitrate concentration (mg L^{-1}), IR the daily water-intake rate (L d^{-1}), BW the body weight (kg) and RfD the oral reference dose (1.6 mg kg^{-1} d^{-1}; USEPA IRIS, 1991). By convention an HQ at or below one is taken to signal a negligible risk and an HQ above one a potential adverse effect (Adimalla & Qian, 2019; Liu et al., 2011). Because water intake relative to body weight is what makes the young more exposed, we evaluate the risk separately for five age groups: infants, young children, children, teenagers and adults.

2.3 Monte Carlo simulation

Each uncertain input was represented by a probability distribution and sampled 10,000 times for every age group (Table 1), following established good practice for Monte Carlo techniques in health-risk assessment (Burmaster & Anderson 1994; Kentel & Aral 2005). The nitrate concentration was drawn, with replacement, from the 25 measured values. The ingestion rate and body weight were drawn from normal distributions centred on the age-specific means of the USEPA Exposure Factors Handbook (Kavcar et al., 2009; USEPA, 2011), with coefficients of variation of 20 % and 15 % respectively and truncated at physically plausible positive bounds; the reference dose was held fixed. For each of the 10,000 iterations we computed the hazard quotient, and from the resulting sample we read off, per age group, the full HQ distribution, its percentiles (P5, P25, P50, P75, P95), its mean, and the probability of an unacceptable risk, P(HQ > 1) - the quantity a deterministic calculation cannot provide.

Table 1 Input distributions used in the Monte Carlo simulation (10,000 iterations per age group).

Input	Distribution	Central value	Spread	Source
Nitrate C (mg L^{-1})	Empirical (resampled)	mean 44.3 (8.6–100)	measured	This study (n = 25)
Ingestion rate IR (L d^{-1})	Normal (truncated)	0.64 / 0.75 / 1.0 / 1.4 / 2.0	CV 20 %	USEPA (2011)
Body weight BW (kg)	Normal (truncated)	6.9 / 15 / 24 / 45 / 70	CV 15 %	USEPA (2011)
Reference dose RfD	Constant	1.6 mg kg^{-1} d^{-1}	—	USEPA IRIS (1991)
Central values for IR and BW are listed for infants / young children / children / teenagers / adults.				

2.4 Sensitivity analysis

To find out which input actually drives the hazard quotient, we computed the Spearman rank correlation between each sampled input and the resulting HQ across the 10,000 iterations - a robust, distribution-free measure that is standard in probabilistic risk work and closely related to variance-based sensitivity indices (Saltelli et al., 2008; Sobol, 2001). A larger absolute coefficient means the input exerts a stronger control on the risk; its sign gives the direction. All computations: the Monte Carlo simulation, the percentile and exceedance-probability estimates and the sensitivity analysis, were carried out in the R statistical environment (R Core Team).

3 Results and discussion

3.1 The shape of the risk

Perhaps the most telling result is not a number but a shape. In every age group the simulated hazard quotient is strongly right-skewed (Fig. 1; Table 2): a broad body of moderate values with a long tail of high ones, inherited directly from the skewed distribution of nitrate in the aquifer. The median HQ falls steadily with age 2.48 for infants, then 1.35, 1.11, 0.81 and 0.76 for young children, children, teenagers and adults respectively, but the spread is what a single deterministic figure would miss. For infants the 5th–95th-percentile range runs from 0.59 to 5.83, so that even in the most favourable one-in-twenty case the infant hazard quotient is already close to unity, while in adults the median sits below the threshold and only the upper tail crosses it. Making that spread explicit, rather than collapsing it, is the whole point of the probabilistic approach (Burmaster & Anderson 1994).

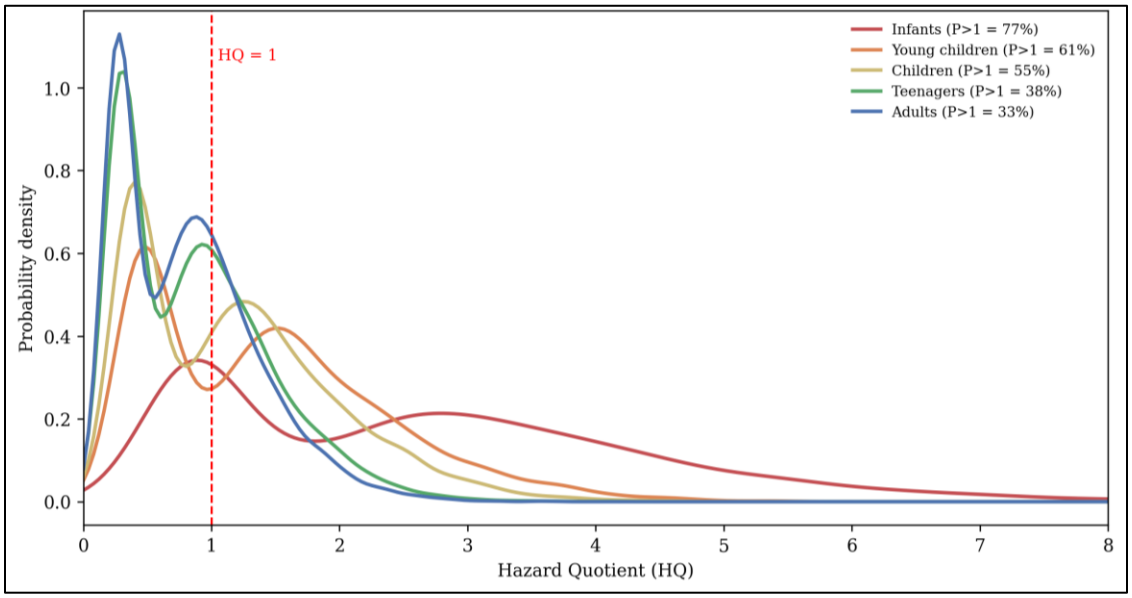


Fig. 1 Monte Carlo probability distributions of the nitrate hazard quotient for the five age groups (10,000 iterations). The dashed line marks the risk threshold HQ = 1; the legend gives the probability P(HQ > 1)

Table 2 Percentiles, mean and exceedance probability of the simulated hazard quotient by age group.

Age group	P5	P25	P50	P75	P95	Mean	P(HQ>1) %
Infants	0.59	1.06	2.48	3.72	5.83	2.65	77.2
Young children	0.32	0.58	1.35	1.99	3.17	1.43	61.4
Children	0.27	0.47	1.11	1.65	2.61	1.18	54.8
Teenagers	0.20	0.35	0.81	1.23	1.96	0.88	37.8
Adults	0.19	0.33	0.76	1.14	1.80	0.81	33.3

3.2 How likely is an unacceptable risk?

Turning the distributions into a single, policy-ready number gives the probability that the hazard quotient exceeds one: 77 % for infants, and 61, 55, 38 and 33 % for young children, children, teenagers and adults (Fig. 2). Put plainly, for a randomly chosen location and a randomly chosen infant of the oasis population, an unacceptable nitrate exposure is more likely than not - a statement that speaks to decision-makers far more directly than a count of samples above a threshold. The probabilistic estimates sit slightly above their deterministic counterparts (72 % for infants in the companion study) because the simulation samples the variability of intake and body weight and so captures the upper tail of exposure that a mean-value calculation leaves out. The same ordering - risk falling monotonically from infants to adults - has been reported for nitrate in comparable settings (Mohanta et al., 2026; Sakizadeh & Zhang, 2020; Zhang et al., 2018).

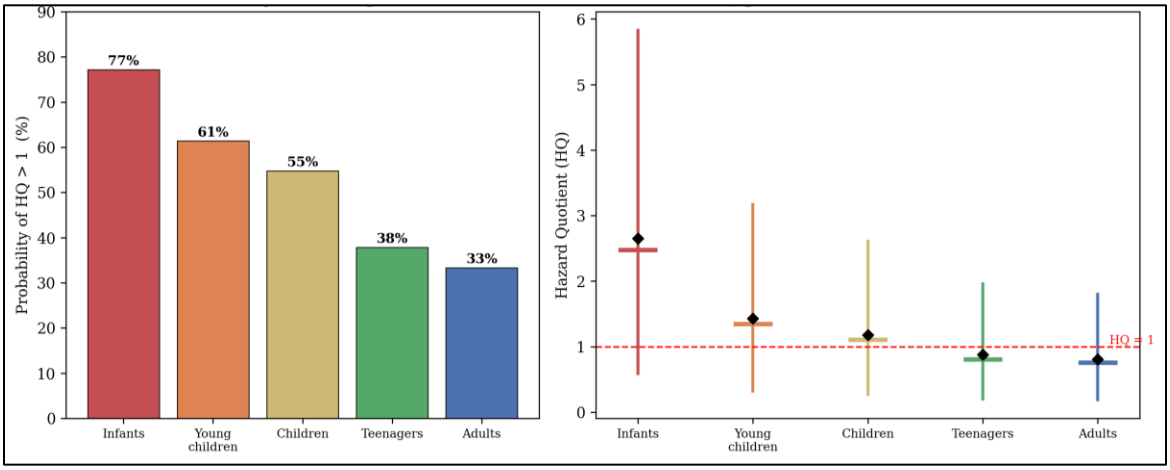


Fig. 2 (a) Probability of an unacceptable non-carcinogenic risk, P(HQ > 1), by age group; (b) percentile ranges of the simulated hazard quotient (bar = P5–P95, thick mark = median, ◆ = mean). The dashed line marks HQ = 1

3.3 What drives the risk

If the risk is indeed genuine, the next issue that naturally arises is, what should be done about it? Moreover, the sensitivity analysis provides a clear response to it. Across all five age groups the nitrate concentration overwhelmingly controls the hazard quotient (Spearman $\rho \approx 0.91$), leaving the ingestion rate ($\rho \approx 0.29$) and body weight ($\rho \approx -0.21$) far behind (Fig. 3). The negative sign on body weight is exactly what one expects, since a heavier person dilutes the same dose. Similar analyses of nitrate risk consistently reach the same verdict (Paladino et al., 2018; Rajasekhar et al., 2018; Sadler et al., 2016; Sakizadeh & Zhang 2020). The practical message is unusually direct: the risk is set far more by how much nitrate the water carries than by the details of who drinks it, so effort spent reducing the nitrate concentration - through source control, blending or treatment - will lower the risk far more effectively than any refinement of the exposure assumptions.

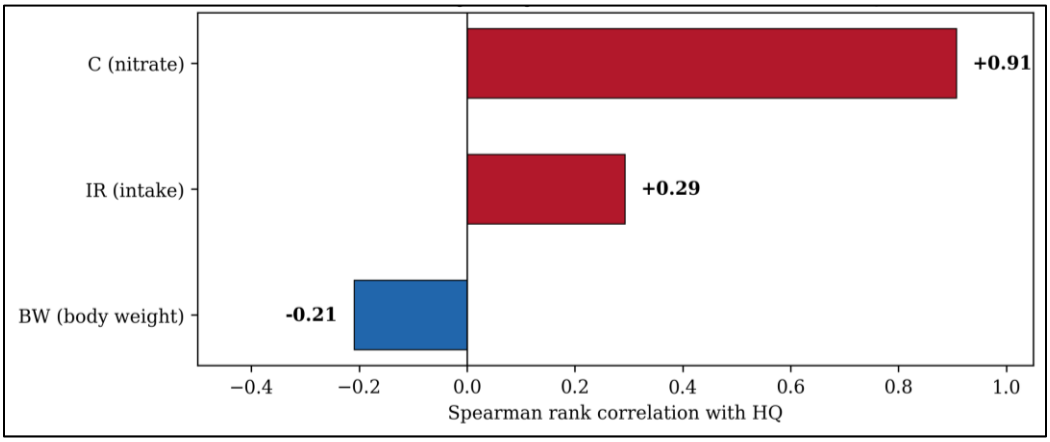


Fig. 3 Sensitivity of the nitrate hazard quotient to its inputs, expressed as the Spearman rank correlation between each sampled input and the simulated HQ (average of the five age groups)

3.4 Implications, and a note of caution

Taken together, the probabilistic results reinforce the deterministic diagnosis and give it edges: nitrate poses an unacceptable non-carcinogenic risk to a large share of the young population of the Adrar–Timimoun oases, most acutely to infants, and that risk is governed by the nitrate concentration itself. The finding matters beyond the acute methaemoglobinaemia endpoint, because the epidemiological evidence now points to health effects at concentrations well below the guideline (Schullehner et al., 2018; Ward et al., 2018). It also aligns with the wider literature on nitrate risk in arid groundwater, which repeatedly identifies children as the most sensitive group and the nitrate concentration as the dominant lever (Hallal et al., 2026; Mohanta et al., 2026; Su et al., 2013; Wu & Sun, 2016; Zhang et al., 2018). Practically, this argues for protecting well-heads, curbing fertiliser and effluent inputs, and providing nitrate-safe water for infant feeding in the worst-affected sectors, backed by routine monitoring.

Two caveats keep the numbers in perspective. The hazard quotient is a screening ratio, not a probability of disease, and it treats measured concentrations as stable in time and ignores nitrate taken in through food; the exposure factors, moreover, are international defaults rather than locally measured intakes and body weights (Kavcar et al., 2009; USEPA, 2011). Local exposure surveys, seasonal sampling and, ideally, isotopic source tracing would tighten the estimate. Until then, and given how strongly the risk tracks the nitrate concentration, a precautionary stance for infant feeding in the high-nitrate wells is the reasonable course.

4. Conclusion

By treating nitrate and human exposure as distributions rather than single numbers, this Monte Carlo assessment puts a probability on a risk that a deterministic calculation could only assert. In the Continental Intercalaire groundwater of the Adrar–Timimoun oases, the hazard quotient is strongly right-skewed and its median falls from 2.48 in infants to 0.76 in adults; the chance of exceeding the risk threshold is 77 % for infants and declines to 33 % for adults. The sensitivity analysis leaves little room for doubt about where to act: the nitrate concentration drives the risk (Spearman $\rho \approx 0.91$), far more than any exposure factor. The probabilistic lens therefore does not replace the deterministic verdict so much as give it confidence intervals and a target—pointing squarely at reducing nitrate, and at protecting the youngest consumers first, as the most effective response, supported by continued monitoring of this irreplaceable aquifer.

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