Strategies for Reducing Exposure to Groundwater Nitrates in Drinking Water

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About this Document

This document was developed in response to NCRC collaborator questions on the benefits, tradeoffs, efficacy, and costs of different approaches to nitrate treatment. The following sections discuss strategies for reducing exposure to nitrates in household drinking water with a focus on drinking water treatment. Aquifer remediation (treatment) is discussed briefly in Appendix A under 'Scales of Treatment Systems', but was not the primary focus of this document. Some of the treatment methods discussed (e.g., denitrification) are also commonly used in wastewater treatment. However, given the different issues faced by drinking water and wastewater treatment systems, wastewater treatment is not addressed in the current document, but is flagged as a potential topic for future work.

Overview of Treatment and Non-Treatment Approaches

Effective management of groundwater nitrate requires a multi-faceted approach to reduce both current exposure to groundwater nitrates and the amount of excess nitrate entering groundwater systems. Short, medium, and long-term strategies at the household, water system, and regional scales are needed and often include both treatment and non-treatment options (Figure 1) as well as changes in policy and funding.[1] Testing, education, and behavior change play a critical role in the uptake of both treatment and non-treatment management strategies.

This document shares a general framework for classifying nitrate management approaches (Figure 1) and information on how other states have prioritized across different approaches. Appendix A discusses benefits and challenges, efficacy, and costs associated with different types of nitrate treatment systems, with a focus on drinking water treatment. Appendix B includes a general overview of non-treatment water management options related to water system operations (e.g., alternative sources). Changes in policy and regulations have also played a critical role in managing nitrates in other locales. Examples of policy approaches are included in the companion case studies.[2]

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[1] Addressing Nitrate in California's Drinking Water Project
https://watershed.ucdavis.edu/project/addressing-nitrate-california%27s-drinking-water
[2] Kearl (2023) Responses to nitrate contamination in groundwater: Case studies from Montana, California, and Washington. Northwest Climate Resilience Collaborative.

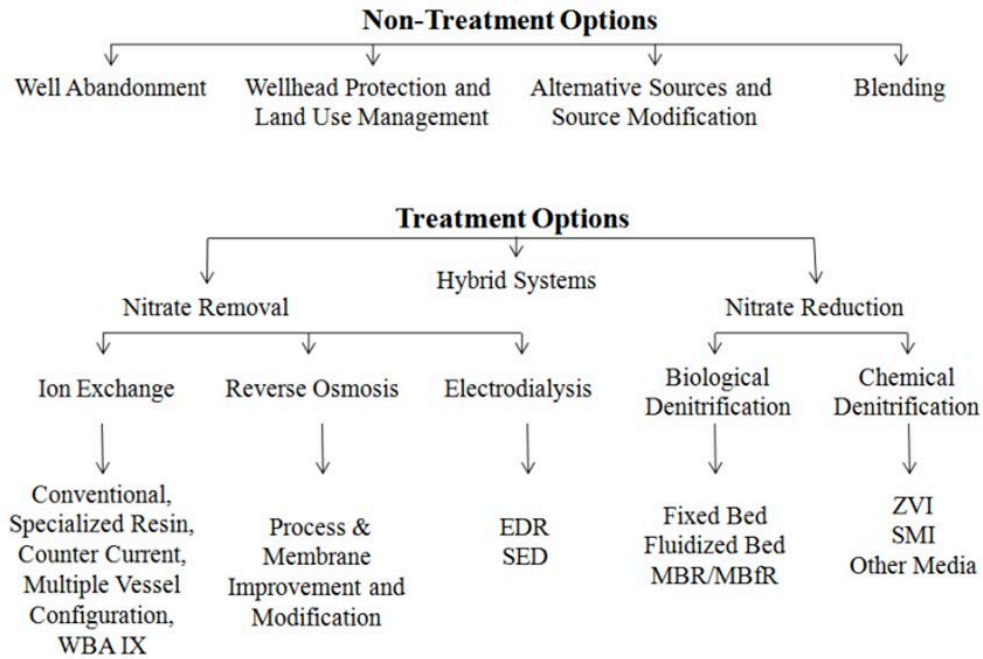

Figure 1. Classification of Nitrate Management Options.
Source: Jensen and Darby (2012) Technical Report 6: Drinking Water Treatment for Nitrate

Box: Addressing Nitrate in California's Drinking Water

The California State Water Resources Control Board (SWRCB) commissioned the Center for Watershed Sciences at the University of California, Davis (UC Davis) to conduct a comprehensive study on nitrate contamination in groundwater. This study produced a series of eight technical reports (below) that were ultimately key references used to motivate and inform state level guidance and policy, including the development of a report by the SWRCB on their preferred alternatives for bringing small water systems into compliance with federal and state Safe Drinking Water Act water quality standards. These eight reports are cited extensively throughout this document.

Addressing Nitrate in California's Drinking Water, Technical Report and Data:

- Executive Summary
- Technical Report 1 - Overview
- Technical Report 2 - Sources of Nitrate in Groundwater
- Technical Report 3 - Reducing Sources of Nitrate in Groundwater
- Technical Report 4 - Nitrate Occurrence in Groundwater
- Technical Report 5 - Remediation of Groundwater Nitrate
- Technical Report 6 - Treatment of Nitrate in Drinking Water
- Technical Report 7 - Susceptible Population and Alternative Water Supplies
- Technical Report 8 - Funding and Policy Options
- Data for Nitrogen Sources and Loading to Groundwater in Tulare Lake Basin and Salinas Valley

Evaluating and Prioritizing Nitrate Management Approaches

Reducing exposure to groundwater nitrates requires a holistic approach to reduce both current exposure to groundwater nitrates and the amount of excess nitrate entering groundwater systems. However, deciding what to prioritize when, and where, is a perennial challenge. This section briefly discusses Washington and California's positions on the role of treatment and non-treatment approaches for reducing exposure to groundwater nitrates. The following appendices discuss the benefits, tradeoffs, and challenges of specific treatment and non-treatment approaches to managing groundwater nitrates in greater detail.

Washington

A review by the Washington Department of Health (DOH) found that, in the 45 small water systems treating for nitrates east of the Cascades, there were 32 separate treatment plant failures during the 2014-16 period. In response to this finding, DOH notes,

> "Treatment may be relatively easy to construct, but it is challenging to operate below the nitrate MCL every day, year after year. We believe non-treatment alternatives, wherever feasible, are a better long-term solution to nitrate contamination."[3]

California

In their evaluation of using POE/POU[4] systems for Safe Drinking Water Act (SDWA) compliance, the California State Water Resources Control Board (SWRCB) takes a similar position to the Washington DOH, stating,

> "Alternatives such as connection to a nearby community water system, a new source, centralized treatment, or a dual distribution system should be thoroughly considered and exhausted as potential solutions before POU/POE device installation because they are considered more sustainable and equitable solutions."[5]

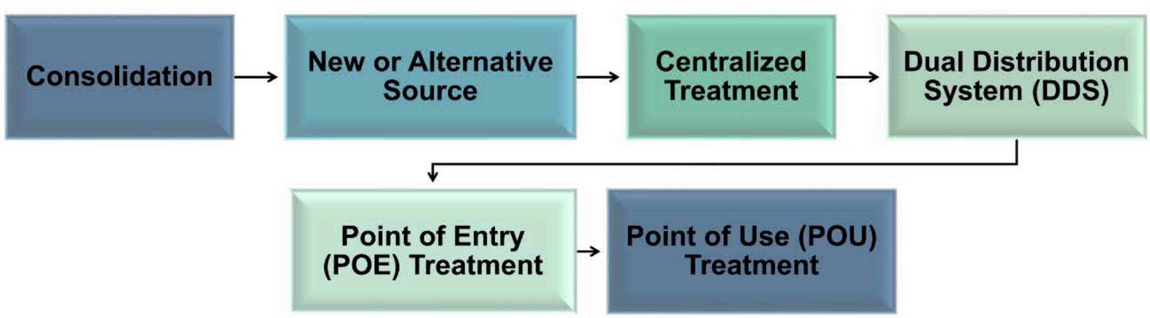

Figure 2. Preferred Alternative Flow Chart for SDWA Water Quality Compliance.

[3] Washington Department of Health (2018) Guidance Document - Nitrate Treatment and Remediation for Small Water Systems (pg 13) https://doh.wa.gov/sites/default/files/legacy/Documents/Pubs//331-309.pdf
[4] Point of Use (POU) systems treat water at the location in the household where the water is being accessed for consumption, typically a kitchen sink. Point of Entry (POE) systems treat water at the point where it enters the household.
[5] California State Water Resources Control Board (SWRCB) (2023) Point of Use/Point of Entry Report (pg 27) https://www.waterboards.ca.gov/safer/docs/2023/2023-POU-POE-report.pdf

Source: California State Water Resources Control Board (SWRCB) (2023) Point of Use/Point of Entry Report

The SWRCB's preferred alternatives for SDWA compliance are outlined in their preferred alternative flow chart (Figure 2). In short, it is preferred that non-compliant water systems first consider consolidating with nearby, compliant water systems. Tools such as the Drinking Water System Outreach Tool[6] are being developed to help make those connections and identify at-risk systems. If consolidation is not possible due to challenges such as distance, supply, or water quality issues, the next preferred alternative is connecting to a new or alternative source such as a deeper well or obtaining rights to surface water. If there is no alternative source, the SWRCB recommends centralized treatment. Centralized treatment is a lesser preferred alternative because of the cost, capacity, and O&M challenges noted above. As Washington DOH observed, these challenges can be especially pronounced for small systems. Dual distribution systems (DDS) supply drinking water from a treated source while water for other household uses is supplied via an existing well or other source. Cost and technical feasibility challenges have limited the use of DDS thus far. POE and POU systems are the least preferred alternatives due to equity, treatment reliability, and cost issues. In California, variances allowing systems to use POE/POU for water quality compliance are only granted for three years at a time, with the expectation that systems are working to implement other more durable and equitable solutions during that time period. Two key requirements in California's water system POE/POU program are a robust, professional O&M program for maintaining and/or replacing in-home systems and regular monitoring of treated water at households.

Private Wells and Preferred Alternatives

Private wells are often most vulnerable to groundwater nitrate issues, but are not subject to state and federal drinking water quality requirements. As such, the Washington and California reports cited above focus on strategies for established water systems falling under their regulatory jurisdiction. However, the broader lessons and preferred alternatives are still equally relevant to households supplied via private wells. Common household-scale nitrate management practices such as water deliveries and household treatment can increase access to safe water in the short term, but are often unreliable in the long run due to operation and maintenance, scalability, and staffing challenges.[7,8,9,10] Likewise, these approaches typically cost more on a per household basis and create significant equity issues due to the additional cost, maintenance, and monitoring burdens they place on households. Given these limitations, parallel efforts such as the California SWRCB Safe and Affordable Funding for Equity and

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[6] Drinking Water System Outreach Tool https://gispublic.waterboards.ca.gov/portal/apps/webap

[7] Washington Department of Health (2018) Guidance Document - Nitrate Treatment and Remediation for Small Water Systems https://doh.wa.gov/sites/default/files/legacy/Documents/Pubs//331-309.pdf

[8] California State Water Resources Control Board (SWRCB) (2023) Point of Use/Point of Entry Report (pg 27) https://www.waterboards.ca.gov/safer/docs/2023/2023-POU-POE-report.pdf

[9] Wu, Jishan, Miao Cao, Draco Tong, Zach Finkelstein, and Eric M. V. Hoek. 2021. "A Critical Review of Point-of-Use Drinking Water Treatment in the United States." *Npj Clean Water* 4 (1): 1–25. https://doi.org/10.1038/s41545-021-00128-z.

[10] Lane, Kaycie, David Reckhow, John Tobiason, and Emily Kumpel. 2023. "Triple-Bottom-Line Approach for Comparing Point-of-Use/Point-of-Entry to Centralized Water Treatment." *AWWA Water Science* 5 (2): e1320. https://doi.org/10.1002/aws2.1320.

Resilience (SAFER) program are directing funding and resources toward identifying and connecting households to better performing public water systems.

Appendix A: Treatment Options for Nitrate Management

Overview of Nitrate Treatment Methods

Current treatment alternatives typically reduce nitrate concentrations in drinking water by one of three approaches: (1) Removal via physical or chemical processes; (2) Conversion of nitrate to nitrogen gas; or (3) Blending to reduce nitrate concentrations.[11,12,13] This section includes a brief summary of common nitrate treatment methods in drinking water and a comparison of treatment alternatives (Table A.1).

Ion Exchange (IX)

Ion exchange is the most commonly used nitrate treatment method. In ion exchange, a selective treatment resin is used to ‘capture’ nitrate ions (NO_3^-). This is similar to how water softeners work, except the treatment resin captures nitrate ions rather than ‘hardness’ ions such as magnesium and calcium. Ion exchange requires periodic regeneration of the treatment resin with a concentrated salt solution to open up binding sites for additional nitrate ions. Practically, this means that ion exchange produces a highly concentrated waste stream of salt and nitrate each time the resin is regenerated. Disposing of this waste brine in a safe and sustainable manner can be a challenge and is an area of active research. Regular monitoring is required to ensure treatment resins are regenerated at frequent enough intervals.

Reverse Osmosis (RO)

Reverse osmosis is the second most common method of nitrate treatment. Reverse osmosis uses a selective membrane that allows passage of water molecules while retaining nitrate ions (and other molecules unable to pass through the membrane). Reverse osmosis is commonly used to treat brackish and saline waters. Pre-treatment is often required to prevent premature membrane failure (fouling and scaling). Similar to ion exchange, reverse osmosis produces a concentrated waste stream and can be energy intensive, though both topics are areas of active research.

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[11] Fernández-López, José A., Mercedes Alacid, José M. Obón, Ricardo Martínez-Vives, and José M. Angosto (2023) “Nitrate-Polluted Waterbodies Remediation: Global Insights into Treatments for Compliance.” Applied Sciences 13 (7): 4154. https://doi.org/10.3390/app13074154.

[12] Washington Department of Health (2018) Guidance Document - Nitrate Treatment and Remediation for Small Water Systems https://doh.wa.gov/sites/default/files/legacy/Documents/Pubs//331-309.pdf

[13] Jensen and Darby (2012) Technical Report 6: Drinking Water Treatment for Nitrate https://watershed.ucdavis.edu/sites/g/files/dgvnsk8531/files/products/2022-05/Drinking%20Water%20Treatment.pdf

Electrodialysis (ED)

Electrodialysis is more commonly used for desalination and its application in nitrate treatment has been more limited to date. Electrodialysis (or electrodialysis reversal (EDR)) passes an electric current through a series of positively and negatively charged ion exchange membranes which attract charged ions, such as nitrate. Similar to ion exchange and reverse osmosis, a concentrated waste stream is produced.

Denitrification (Biological and Chemical)

Nitrate is converted to other nitrogen species such as nitrogen gas using microbes (biological) or metals (chemical). Biological denitrification (BD) is more commonly used in Europe and requires reasonably high operational capacity to ensure biological processes continue functioning effectively without other detrimental impacts on water quality (e.g, turbidity, bacterial counts). A benefit of biological denitrification is the lack of concentrated waste stream to manage. Research on scaling chemical denitrification (CD) in drinking water applications is ongoing.

Blending

Blending dilutes nitrate contaminated water by mixing it with water from an alternative supply, such as water from a deeper well with lower nitrate concentrations. Due to constraints in the quantity of water available for blending, this approach is typically only used when nitrate concentrations are slightly above the nitrate maximum contaminant level (MCL) of 10 mg/L. In some contexts, blending is considered a non-treatment option.

Table A.1. Washington Department of Health (DOH) Summary of Current Nitrate Treatment Alternatives.

Table 2-1 Summary of Nitrate Treatment Alternatives

	Treatment				
Factor	**Blending**	**Ion Exchange**	**Reverse Osmosis**	**Electrodialysis**	**Engineered Biological Treatment**
Installations	Many	Many	Few	None is U.S. Several in Europe	Few
Pretreatment Required	None	Sometimes	Significant	Sometimes	None
Total Life Cycle Cost	Variable	Moderate	High	High	Moderate
Performance-Limiting Raw Water Quality Parameters[1]	Mass-balance flow from blended sources so that nitrate at entry point to dist. system is less than MCL	Iron, manganese, , sulfate, bicarbonate hardness, alkalinity, organic carbon, turbidity, and total dissolved solids	Total dissolved solids, turbidity, silt density index, total hardness, pH, iron, manganese, organic carbon, sulfate and hydrogen sulfide, chlorine	Iron, manganese, turbidity, total dissolved solids, hydrogen sulfide, total hardness, pH, alkalinity, chlorine	Optimum pH 7-8.5. Temperature: 5-30°C
Post Treatment	None	pH adjustment may be required	pH and alkalinity adjustment may be required	pH adjustment may be required	Filtration, disinfection, and taste and odor control
Waste Disposal	None	Salt brine and rinse water	Concentrate	Concentrate	Biological solids
Feasibility of Automation	Good	Good	Good	Good	Good
Process Start-up Time	Short	Short	Short	Short	Long

[1]Consult with the manufacturer on recommended water quality parameter testing and acceptable water quality values for their equipment and process.

Source: Washington Department of Health (2018) Guidance Document - Nitrate Treatment and Remediation for Small Water Systems (pg 16) https://doh.wa.gov/sites/default/files/legacy/Documents/Pubs//331-309.pdf

Note: Engineered biological treatment is the same as biological denitrification.

Treatment Efficacy and Tradeoffs of Treatment Alternatives

Treatment efficacy is a measure of how effective a treatment method is in reliably meeting the desired water quality goal (e.g., reducing nitrate levels to less than 10 mg/L). Treatment efficacy varies across alternatives and depends on many factors, including influent nitrate concentrations. Actual system design should take into account the full range of water quality and treatment considerations that can impact treatment efficacy. However, as a general rule, blending (dilution) can be used when influent concentrations are around 11-13 mg/L. Ion exchange is most effective at treating nitrate concentrations up to approximately 20 mg/L (and sometimes higher).[14] Reverse osmosis and biological denitrification can be used to treat higher concentrations of nitrate. The California SWRCB generally recommends against the long-term use of point of use (POU) systems when influent nitrate concentrations exceed 25 mg/L.[15] This is due to the technical and operational complexities of achieving this level of sustained performance in a POU system. Many of the common nitrate treatment approaches are also effective at removing other common groundwater contaminants such as salinity (TDS), arsenic, and chromium (Figure A.1). Treatment of these additional contaminants is an important potential co-benefit of nitrate treatment and we recommend reviewing the whole suite of local groundwater quality concerns in the design process.

Multiple considerations impact the realized efficacy and longevity of nitrate treatment systems (Figure A.1). Waste management is a major challenge of IX and RO systems. Successful operation of denitrification-based systems for potable water requires significant capacity and expertise in operating and maintaining these treatment processes, which is why they are generally not considered a viable option for POU or very small systems.

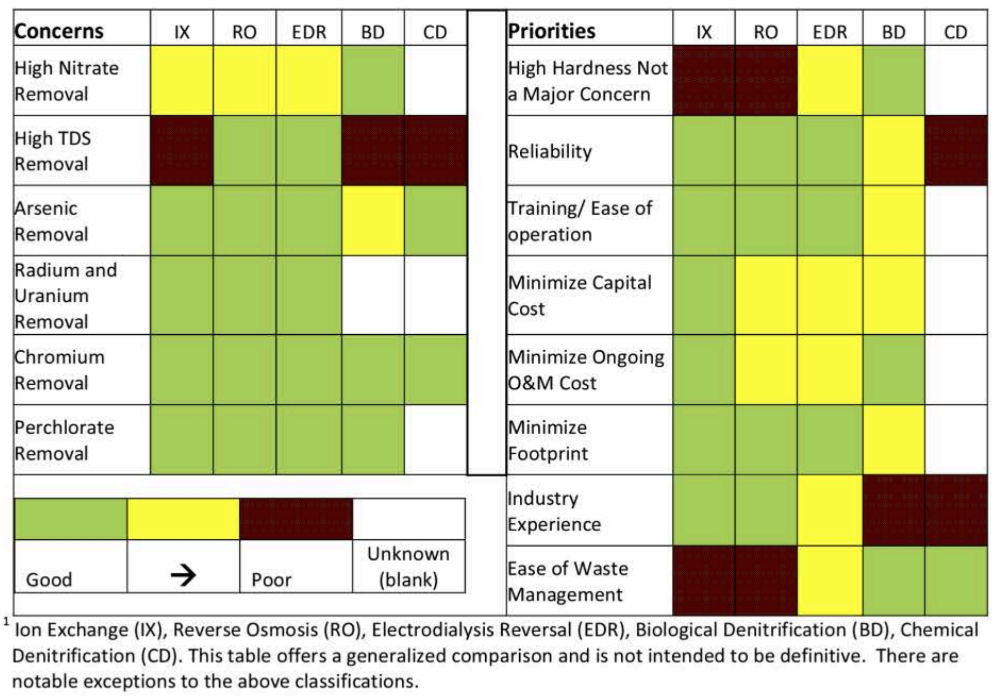

Figure A.1. Comparison of Nitrate Treatment Approaches. (a) Effectiveness in Removing Multiple Contaminants and (b) Relative Significance of Common Constraints and Tradeoffs by Treatment Approach. Source: Jensen and Darby (2012) Technical Report 6: Drinking Water Treatment for Nitrate (pg 129)

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[14] Jensen, Vivian B, Jeannie L Darby, Chad Seidel, and Craig Gorman. 2012. “Technical Report 6: Drinking Water Treatment for Nitrate.” Addressing Nitrate in California’s Drinking Water With a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. Davis, CA: Center for Watershed Sciences, University of California, Davis.

[15] California State Water Resources Control Board (SWRCB) (2023) Point of Use/Point of Entry Report (pgs 15, 39) https://www.waterboards.ca.gov/safer/docs/2023/2023-POU-POE-report.pdf

Scales of Treatment Systems

The treatment processes described above can be used in multiple scales of treatment systems (Table A.2). In practice, treatment typically occurs through point of use (POU)/point of entry (POE) systems or at a centralized water treatment plant. Different scales of treatment and relevant benefits and challenges are summarized in Table A.3.

Table A.2. Scale of System and Use of Different Treatment Methods

	Ion Exchange	Reverse Osmosis	Electrodialysis	Denitrification
POE/POU	X	X		
Water Treatment Plant	X	X	Experimental	X/ Experimental[2]
Aquifer Remediation[1]	No current aquifer scale remediation projects for nitrate. Treatment technologies listed have been used to remove other contaminants at smaller scales (e.g., specific contaminant plume).			

1. Researchers at UC Davis conducted a comprehensive assessment of the potential for using aquifer remediation to address nitrate issues in the Tulare Lake Basin (~700 mi^2) and Salinas Valley (~1000 mi^2). Their study found that the scale of remediation would be more expensive and less effective than other approaches that more directly address nutrient inputs and drinking water quality. This continues to be an area of active research. Addressing Nitrate in California's Drinking Water: Technical Report 5 - Remediation of Groundwater Nitrate | Center for Watershed Sciences discusses aquifer remediation in depth.
2. Biological denitrification is used some in Europe, but its adoption in the United States for drinking water treatment has been more limited. Chemical denitrification for nitrate treatment in drinking water is still in a research phase.

Table A.3. Description, Benefits, and Challenges of Different Scales of Nitrate Treatment.

Scale	Description	Benefits	Challenges
Household (POU/POE)	Water is treated at the sink prior to consumption (POU) or at the point of entry into the household (POE).	● Can be used to treat water from private wells. ● POU systems are obtainable through local channels/retailers. ● Can sometimes remove a broader range of contaminants beyond nitrate.	● Places burden of treatment (cost, effort, monitoring, etc) on individual households. ● POU/POE systems often fail or underperform over time (relative to centralized treatment) when monitoring and/or O&M are neglected . ● Requires robust monitoring and O&M program to achieve the same level of reliability as centralized systems. ● Lacks economy of scale of water system-level approaches. ● Discharge of concentrated ‘reject water’ to septic systems. ● Selecting the appropriate type of treatment system requires consideration of well water quality and chemistry (e.g., Reverse osmosis is often recommended if nitrate levels exceed 30 mg/L). ● POE systems require additional monitoring to ensure no adverse reactions with premise plumbing (e.g., lead in fixtures/solder).

Scale	Description	Benefits	Challenges
Water System	Nitrate is removed by community/municipal water system treatment processes.	● Economy of scale (relative to POU/POE). ● Water agencies have more capacity to monitor water quality, operate and maintain treatment. ● Some treatment processes also remove other contaminants and may help address future drinking water standards (e.g., PFAS) and other contaminants (e.g., arsenic, agricultural chemicals). ● Drinking water systems that are experiencing elevated or increasing nitrate concentrations, but not exceeding water quality standards may still find benefits in being proactive about nitrate treatment (e.g., heading off future exceedances, removing other contaminants of local concern)	● Time to implementation is longer than POU and typically requires securing loan/grant funding (e.g., Drinking Water State Revolving Funds) to cover upfront costs. ● Most current local treatment systems only include disinfection. Additional technical/financial capacity would be needed to support nitrate treatment. ● It is costly to safely dispose of concentrated waste streams from ion exchange and membrane processes.

Scale	Description	Benefits	Challenges
Aquifer Remediation	Groundwater is pumped, treated for nitrate, and reinjected into the aquifer. In situ treatment (within aquifer) is also sometimes used to treat contaminants in place by transforming the contaminant into neutral or less harmful substances.	● Would be a major scientific breakthrough if done effectively and affordably. ● Could potentially shift burden of the cost of treatment away from water systems and households.	● Unclear whether it would lead to the desired improvements in drinking water quality. ● Requires treatment of much larger volumes of water than the amount that would be treated through water system and/or POE/POU scale systems. ● Typically better suited to treating geographically constrained plumes of pollution/point sources. ● Treated water is reinjected and blends with groundwater (potentially recontaminating treated water). ● Treatment byproducts of in situ remediation may still be undesirable for drinking water quality (e.g., high bacterial counts associated with bioremediation, organics that react with chlorine to form disinfection byproducts during treatment). ● Management of waste stream from ex situ remediation. ● Very expensive (more commonly used to remediate toxics). ● This approach has never been tested at an aquifer scale for nitrate remediation.

Estimated Costs of Standard Nitrate Treatment Approaches

The cost of treating nitrates in drinking water varies widely. Factors such as system size, characteristics of the water being treated, and local options for managing waste streams associated with treatment processes all impact realized costs in practice. Larger capacity systems typically cost more overall, but less per gallon of water treated. Ion exchange and reverse osmosis are the two treatment technologies most commonly used to remove nitrate from drinking water and are the focus of the tables shared below. Estimates on the annualized capital and operation and maintenance (O&M) costs of nitrate treatment systems for different sizes of drinking water systems are shared in the tables below. Cost data are shared in the units they were provided in and have not been updated to 2024 dollars.

"*Technical Report 6: Drinking Water Treatment for Nitrate*" includes estimates (in 2010 dollars) comparing the capital and O&M[16] costs of ion exchange and reverse osmosis in different sizes of public water systems (Table A.4). While there are economies of scale, cost ranges vary widely though ion exchange was typically less expensive in these types of systems. Influent water chemistry and the presence of other contaminants requiring treatment are key design considerations (in addition to cost).

Table A.4. Estimated Capital and O&M Costs for Different Sizes and Types of Nitrate Treatment Systems.

System Type	System Flow**	<0.5 MGD	0.5-5 MGD	5+ MGD
Ion Exchange	Annualized Capital Cost ($/1000 gal)	0.37-1.21	0.28-0.94	0.28-0.61
	O&M Cost ($/1000 gal)	0.60-4.65	0.46-1.25	0.37-0.87
	Total Annualized Cost ($/1000 gal)	0.97-5.71	0.74-2.19	0.65-1.44
	Sources of Cost Data***	1	2,3	3,4,5
Reverse Osmosis	Annualized Capital Cost ($/1000 gal)	3.51-5.17	1.00-1.30	0.95
	O&M Cost ($/1000 gal)	1.46-16.16	1.22-2.01	1.63
	Total Annualized Cost ($/1000 gal)	5.73-19.70	2.52-3.21	2.58
	Sources of Cost Data***	6,7	3,8	3

Source: Jensen and Darby (2012) Technical Report 6: Drinking Water Treatment for Nitrate

** When available costs are based on actual system flow rather than design capacity.
*** All cost data sourced from Jensen and Darby (2012). Costs have not been updated to 2024 dollars.
See 'Technical Report 6' for details on data sources.
1. Minnesota Department of Agriculture (N.D.), not adjusted to 2010 dollars, 20 year amortization without interest.
2. Guter 1995
3. Conlon et al. (1995)
4. Meyer et al. (2010)
5. Drewry et al. (2010)
6. Walker (N.D.), costs not adjusted to 2010 dollars
7. Personal communication with representatives of two small water systems (2010).
8. Cevaal et al. (1995)

[16] O&M costs in these estimates include the cost of resin or membrane replacement, waste disposal, chemical use, repair and maintenance, power, and labor.

Jensen and Darby also developed hypothetical estimates of nitrate treatment costs for different sizes of systems with varying levels of nitrate contamination (1-3X the MCL) (Table A.6). Treating water with higher influent nitrate concentrations is more expensive due to higher O&M costs. When influent nitrate concentrations are above 2-3X the MCL (approximately 20-30 mg/L), reverse osmosis provides more effective treatment and was used in those estimates.

Table A.6. An Exercise in the Estimation of Treatment Costs Based on Appropriate Technology for Various Nitrate Levels.[1] Source: Jensen and Darby (2012).

System Size (people)	Raw Nitrate Level	Treatment Type	O&M Cost Range (Avg.)[2]	Annualized Combined Cost Range (Avg.)
			$/1000 gallons	$/1000 gallons
Very Small (25 – 500)	1X MCL	Ion Exchange	0.28 – 3.81 (1.22)	0.62 – 4.60 (1.97)
	2X MCL	Ion Exchange	0.35 – 10.48 (2.13)	0.69 – 11.27 (2.88)
	3X MCL	Ion Exchange	0.42 – 17.15 (3.05)	0.76 – 17.94 (3.80)
	3X MCL	Reverse Osmosis	0.22 – 16.16 (4.22)	0.69 – 19.16 (6.64)
Small (501 – 3,300)	1X MCL	Ion Exchange	0.15 – 2.63 (0.87)	0.34 – 2.73 (1.05)
	2X MCL	Ion Exchange	0.19 – 7.23 (1.52)	0.38 – 7.33 (1.70)
	3X MCL	Ion Exchange	0.23 – 11.84 (2.18)	0.42 – 11.94 (2.36)
	3X MCL	Reverse Osmosis[3]	0.23 – 1.15 (0.57)	0.58 – 1.34 (0.93)
Medium (3,301 – 10,000)	1X MCL	Ion Exchange	0.12 – 1.69 (0.84)	0.36 – 2.04 (1.06)
	2X MCL	Ion Exchange	0.15 – 4.65 (1.47)	0.39 – 5.00 (1.60)
	3X MCL	Ion Exchange	0.18 – 7.61 (2.10)	0.42 – 7.96 (2.32)
	3X MCL	Reverse Osmosis[3]	0.91 – 2.76 (1.89)	1.35 – 3.39 (2.59)
Large (10,001 – 100,000)	1X MCL	Ion Exchange	0.13 – 1.39 (0.66)	0.22 – 1.81 (0.97)
	2X MCL	Ion Exchange	0.16 – 3.82 (1.16)	0.25 – 4.24 (1.46)
	3X MCL	Ion Exchange	0.20 – 6.26 (1.65)	0.29 – 6.68 (1.96)
	3X MCL	Reverse Osmosis	0.40 – 2.21 (1.48)	0.73 – 3.67 (2.38)

[1] This table is strictly an example and is not intended to be definitive, but only to suggest how treatment costs might change with increasing nitrate levels. The estimated increase in O&M costs is wide ranging, 25% – 175%, and depends on many factors including water quality parameters, disposal options, resin capacity, resin type, and ion exchange system design. As nitrate levels increase, salt, disposal, and resin costs for IX will increase (O&M). Reverse osmosis costs will increase with increasing TDS, but not at the same rate, this cannot currently be estimated. Depending on other water quality parameters, the costs of IX are predicted to surpass those of RO. In the future, biological denitrification will likely be considered as an option for > 2X the nitrate MCL. Additionally, increasing the number and/or size of resin vessels to address higher nitrate levels would increase capital costs. O&M costs would still increase; in practice the system would be designed to optimize costs. O&M increases were considered here as an example. Actual costs with increasing nitrate levels for specific systems may vary significantly from listed costs and should be assessed by professional engineers.

[2] Increases in O&M are estimated from a limited dataset comprised of vendor cost estimates for IX costs with nitrate levels increasing from just above the MCL to slightly more than double the MCL. All available cost information was included in the 1X MCL scenario as a starting point, including systems with nitrate levels above 1X the MCL.

[3] Limited dataset for the indicated system size and treatment type.

The California SWRCB's 'Drinking Water Point-of-Use Point-of-Entry Report'[17] also includes cost estimates of centralized and POU/POE treatment (for a range of contaminants) (Table A.7). These estimates are intended to capture the full cost of a POU/POE system, including professional O&M, monitoring, and communication with households. Because of the challenges of achieving high levels of treatment with POU ion exchange systems when nitrate concentrations are high, the estimates focused on reverse osmosis as the POU treatment method for nitrate.

Table A.7. Estimated Capital and Annual Operations and Maintenance (O&M) Costs of Reverse Osmosis POU System.

Reverse Osmosis POU	Cost ($)*
Estimated Capital Costs	
Capital Cost per Connection	1500
Installation Labor Cost per Unit ($100/hr)	200
Admin/Project Mgmt	1000
Communication	300
Total Capital	**3000**
Estimated Annual O&M Costs	
Annual O&M per Connection	100
Operator and Communication Labor ($100/hr)	300
Analytical	40-110
Total O&M	**440-510**

*Cost estimates from SWRCB (2023) and were generally provided to the SWRCB by POU vendors.

Juntakut et al. conducted an assessment of the risks and costs of nitrate contamination in domestic wells in Nebraska (Table A.8).[18] Their cost estimates of reverse osmosis and ion exchange nitrate treatment systems are largely based on estimates from Jensen and Darby (see above), but they also expand upon those estimates to include life cycle costs and non-treatment options such as the cost of drilling a new well and bottled water, and make direct comparisons between household and community scale systems. Even at the low end, serving the same number of households with POU/POE systems or water delivery was significantly more expensive than treatment via a community water system serving approximately 3000 households (10,000 individuals).

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[17] The SWRCB POU/POE Report focuses on the feasibility of using POU/POE systems to bring non-compliant small water systems into compliance with SDWA requirements, typically while other longer term solutions are implemented. This includes systems with nitrate issues, but also a host of other common contaminants such as arsenic and 1,2,3-TCP. As such, the report includes treatment methods such as GAC that do not provide effective treatment for nitrates.

[18] Juntakut, Pongpun, Erin M. K. Haacker, Daniel D. Snow, and Chittaranjan Ray. 2020. "Risk and Cost Assessment of Nitrate Contamination in Domestic Wells." *Water* 12 (2): 428. https://doi.org/10.3390/w12020428.

Table A.8. Estimated Cost Per Household (hh) of Point-of-Use Treatment and Per Community System (cs) For Nitrate Removal. Source: Juntakut et al. 2020

Household Options (hh)	Initial Costs Range [1] ($/hh)	Annual O&M Costs Range [1] ($/hh)	Present Value Costs ($PV_{recurring}$) [2] ($/hh)	Life Cycle Costs (*LCC*) ($/hh)
Reverse osmosis	330–1430	110–330 (+ electricity)	1371–4113	1701–5543
Distillation	275–1650	440–550 (+ electricity)	5484–6855	5759–8505
Ion exchange	660–2425	270–470	3365–5858	4025–8283
New well	7200–16,000	-	-	7200–16,000
Bottled water [3]	-	603–1904	7506–23,717	7506–23,717
Community System Options (cs) [4]	**Initial Costs Range [5] ($/cs)**	**Annual O&M Costs Range [5] ($/cs)**	**Present Value Costs ($PV_{recurring}$) [6] ($/cs)**	**Life Cycle Costs (*LCC*) ($/cs)**
Reverse osmosis	8,253,000	2,873,293	35,807,582	44,060,582
Ion exchange	360,000	710,880	8,859,136	9,219,136
Biological denitrification	3,200,140	240,787	3,000,738	6,200,878

[1] Costs have been adjusted to 2010 dollars [30,38,40]. [2] Present value costs ($PV_{recurring}$) are assumed for annualized O&M costs at 5% discount rate over 20 years [38]. [3] Bottled water costs are assumed for two gallons daily per person at $0.25-0.79 per gallon. A household includes 3.3 persons [38]. [4] A community system was assumed to provide water for up to 10,000 individuals. [5] Costs were obtained from [42]. [6] Life cycle costs are assumed for annualized O&M costs at 5% discount rate over 20 years [38].

Appendix B: Overview of Non-Treatment Options

Non-treatment options are wide ranging and often complementary to treatment-based approaches (Table B.1). Wellhead protection and land use management seek to reduce wellhead vulnerability and inputs of nitrates into the system. Alternative sources and source modification are more targeted approaches that aim at improving access to a safe drinking water source. Time from implementation to realization of benefits varies widely across strategies. Planning for non-treatment options should be holistic, addressing both the immediate public health crisis and the longer term need to reduce the amount of nitrate entering the system. This section highlights benefits and tradeoffs of some common non-treatment approaches, but does not discuss these approaches in the same depth as treatment options.[19]

[19] This choice was made only to constrain the scope of the document to specific questions in the companion 'Needs Identification' document and is not at all reflective of the relative importance or efficacy of treatment and non-treatment options. Effective management will address the issue of groundwater nitrates holistically and necessarily includes both treatment and non-treatment options.

Table B.1. Description, Examples, Benefits, and Challenges of Non-Treatment Nitrate Management Approaches for Improving Access to Safe Drinking Water.

Option	Description	Example Strategies	Benefits	Challenges
Well Abandonment	Contaminated well is no longer used as a source of drinking water.		Removes exposure pathway. Potential for connection to higher quality, more reliable water source.	Not a viable solution if no alternative water supply is available.
Wellhead Protection	Targeted protection/armoring and management of activities in the direct vicinity of a water supply well and the broader wellhead supply area.	Building a structure around wellhead. Removing manure stockpile in wellhead supply area.	Can reduce direct contamination of well through increased protection/ armoring/ management in the wellhead supply area. Can help reduce direct sources of contamination (e.g., surface runoff into wellhead). General best practice in well maintenance and operation.	Mitigates impacts from direct sources of nitrate within the wellhead protection zone.
Land Use Management	Reduce nitrate inputs to groundwater system through changes to land management practices (e.g., fertilizer application and irrigation practices).	Only applying fertilizer/ manure during the growing season. Active management of fertilizer application rates using monitoring and assessment of agronomic needs.	Effective land use management strategies will reduce nitrogen inputs into the groundwater system. Land use management is critical component in long-term reductions in in situ nitrate concentrations.	Can require substantial changes in operations and/or more active management. Local soils, crops, hydrology all impact the speed and level of reductions in nitrate concentrations. Can be years before reductions in groundwater nitrates are observed

Option	Description	Example Strategies	Benefits	Challenges
		Changing the types of crops grown/grazing practices.		(due to existing nitrate reservoirs in soil and complex hydrogeology).
Alternative Sources and Source Modification	Connecting to an alternative water supply and/or modifying the existing water source.	Connecting to a public water system with higher quality water. Digging a deeper well to access better quality groundwater. Bottled water delivery	Can help transfer responsibility for monitoring, operation and maintenance to a higher capacity, more resilient water agency (ideally). A diverse supply portfolio is inherently more resilient. Alternative supply may be more resilient to drought impacts and/or overdraft. Bottled water delivery can begin immediately.	Can be expensive. Timelines can be long (particularly for connection/consolidation projects). Connection/consolidation requires community buy-in, partnerships, and cooperation between local entities. May require acquisition of additional water rights. Bottled water deliveries are often unreliable and not a sustainable or equitable long-term source of water.