MONTEREY WATERKEEPER
Santa Barbara CHANNELKEEPER®
San Jerardo Cooperative, INC
California Rural Legal Assistance, Inc.
LEADERSHIP COUNSEL FOR JUSTICE & ACCOUNTABILITY

Chief Deputy Director Karen Mogus
State Water Resources Control Board
1001 "I" Street, 24th Floor
Sacramento, CA 95812

Dear Chief Deputy Director Mogus and Members of the Second Statewide Agricultural Expert Panel,

The undersigned organizations are pleased to submit this literature review of scholarly articles regarding the health and socioeconomic costs of nitrate contamination ("literature review"). This literature review was prepared by Alexandra Hall-Rocha, a graduate student at the University of California, Berkeley and was reviewed by several academic and nonprofit partners. Before the Expert Panel makes recommendations about agricultural nitrogen management practices, it is important for Expert Panelists to understand the health and economic impacts nitrate contamination have on affected residents and the public. Below, we highlight some of the key conclusions in the literature review:

Key Conclusion 1: Nitrate levels are higher in water systems serving disadvantaged communities, particularly in agricultural regions of California. Given the growing body of literature linking nitrate-contaminated water to chronic health conditions, disadvantaged communities have a disproportionate risk of the economic and health impacts associated with nitrate contamination.

Key Conclusion 2: Boiling nitrate-contaminated water increases nitrate concentration due to evaporation, suggesting that preparing foods—such as soup, porridge, beans, coffee, stew—may pose an even higher risk to the consumer than contaminated drinking water.

Key Conclusion 3: Although the federal government set the current maximum contaminant level (MCL) for nitrate at 10 mg/L in 1962 based on studies related to blue baby syndrome, several more recent studies have observed chronic conditions impacting adults associated with exposure to lower nitrate levels, including thyroid disease, various cancers, and birth complications.

The continued presence of nitrate in drinking water and the emergence of associated health risks from lower levels of nitrate concentration exposure raises concerns about the urgency of preventing further nitrogen pollution. Therefore, it is imperative that the Expert Panel urge the State Water Resources Control Board to act quickly and set limits on agricultural nitrogen loading–or risk exposing Californians to both the short- and long-term impacts of the contaminant.

Sincerely,

Rosa Carrillo
General Manager
San Jerardo Cooperative, Inc.

/ / /

Horacio Amezquita
Central Coast Farmer

Corinne Gibson
Staff Attorney
Leadership Counsel for Justice and Accountability

Alexandra Hall-Rocha
Master's Student Candidate

Kjia Rivers
Senior Policy Advocate
Community Water Center

Ted Morton
Executive Director
Santa Barbara Channelkeeper

Natalie Herendeen
Executive Director | Attorney
Monterey Waterkeeper

Iris Stewart-Frey
Environmental Justice and the Common Good Initiative

Elias Rodriguez
Clio Maya-Johnson
Chelsea Tu
California Rural Legal Assistance, Inc.
On behalf of the Comité de Salinas

Sent via email to:

Karen Mogus <karen.mogus@waterboards.ca.gov>
Erika Kalve <erica.kalve@waterboards.ca.gov>
Laleh Rastegarzadeh <laleh.rastegarzadeh@waterboards.ca.gov>
Kelsey Moore <kelsey.moore@waterboards.ca.gov>
Sam Magill <s.magill@csus.edu>

A Literature Review on Health and Socioeconomic Impacts of Nitrate Contamination

Prepared by: Alexandra Hall Rocha, MS Candidate, UC Berkeley, Energy and Resources Group

Contributors: Clio Maya-Johnson, Anthony Shing, California Rural Legal Assistance, Inc.

May 4, 2026

ABSTRACT

Nitrate contamination in drinking water is a pervasive environmental health issue in the United States, particularly in areas with high agricultural activity. Numerous scientific studies demonstrate that people suffer acute and long-term health impacts from exposure to nitrate levels at or above 10 milligrams per liter (mg/L). Growing scientific evidence suggests that chronic exposure at levels below 10 mg/L may also increase the risk of colorectal, bladder, and ovarian cancer, thyroid dysfunction, and adverse birth outcomes. This literature review synthesizes U.S.-based and international epidemiologic studies and assessments of the health and socioeconomic impacts of nitrate contamination, including those affecting disadvantaged communities in California. Studies also show substantial societal costs, including medical expenditures, productivity losses, household adaptation burdens, and expensive water treatment and remediation efforts. Together, the evidence suggests that current regulatory frameworks on fertilizer nitrogen do not adequately protect public health and community well-being, particularly in rural and disadvantaged communities. Because of such inadequacies, nitrate contamination must be addressed with urgency through further regulation.

INTRODUCTION

Nitrate contamination in public and private drinking water systems is a longstanding environmental health issue with both acute and chronic implications. Existing regulatory frameworks were established to prevent infant methemoglobinemia, a condition caused by high nitrate intake. Additionally, emerging research has raised concerns about a broader range of health risks at exposure levels well below the U.S. Environmental Protection Agency's (EPA) Maximum Contaminant Level (MCL) of 10 mg/L, highlighting the urgent need to reduce nitrate pollution into drinking water sources immediately.

Human activity has significantly increased the amount of nitrogen entering the environment (Harter et al., 2012). In California, agriculture is the largest source of nitrogen inputs to the ecosystem and is the dominant contributor of nitrogen in groundwater. In California, a nitrogen assessment reported that nearly 419,000 tons of nitrogen leach into groundwater each year, 88% of which originates from fertilizer and manure applications to cropland (Tomich et al., 2016). Nitrogen from fertilizer and manure may be applied as nitrate (NO_3^-) or converted to nitrate via microbial nitrification; nitrate is the primary form of nitrogen that is leached into groundwater

(Killpack et al., 2022). In California's Tulare Lake Basin and Salinas Valley, UC Davis researchers found that nitrogen application to cropland accounts for 96% of nitrate sources in groundwater (Harter et al., 2012). Over half of this nitrate is attributable to the application of synthetic fertilizer alone. These regions are particularly significant as they are home to 40% of California's irrigated cropland, and over half of its dairy herd, making them relevant to understanding nitrate deposition in California's agricultural regions and the potential exposure for neighboring communities.

Nitrate is considered a legacy contaminant, meaning nitrate in drinking water wells today may have been applied to the surface decades ago. Consequently, nitrate contamination is expected to worsen across the state even if mitigating efforts are implemented today (Harter et al., 2012). With 82% of Californians dependent on groundwater for some of their water supply, and many communities entirely reliant on it, nitrate contamination represents a widespread public health concern in California (California Department of Water Resources, 2026). Communities reliant on untreated, mostly shallow groundwater for domestic use are particularly vulnerable to nitrate. Additionally, while most Californians obtain drinking water from large public systems subject to regulatory standards, private domestic well users are not subject to the same regulatory standards. For instance, water quality testing for domestic private wells is encouraged, but there are gaps in water quality testing requirements, and well owners are often responsible for arranging and paying for testing themselves. As a result, monitoring may be inconsistent, and regular testing can be cost-prohibitive, with individual tests costing up to $200 (UC Merced, n.d.). Thus, households reliant on domestic wells may not know whether they are exposed to high levels of nitrate.

Nitrate-contaminated drinking water poses a risk for consumers. Once ingested, nitrate is partially reduced to nitrite (NO_2^-), which can form N-nitroso compounds (NOCs), many of which are known or probable carcinogens (National Cancer Institute, 2025). Researchers are exploring the association between high nitrate levels and chronic disease. This review examines the relevant literature with respect to the following: (1) the origins of the current MCL, (2) the short and long-term impact of nitrate exposure, (3) risks from dermal and alternate exposure pathways, (4) public health costs, (5) cleanup and remediation costs and (6) the communities most vulnerable to nitrate exposure.

METHODS

This literature review synthesizes evidence from epidemiology, environmental justice, and economics literature to evaluate the challenges posed by nitrate contamination. It draws from historical literature, modern cohort and case-control studies, and health economic assessments relevant to contaminated regions. Studies are based in California, other U.S. states, and some international regions.

Studies were collected through two main databases: PubMed and Web of Science. We searched for terms including "nitrate water contamination" paired with the health outcome ("cancer," "thyroid," "neonatal," "birth"). Additional search terms included "dermal exposure," "infant methemoglobinemia," "nitrate remediation," and "economic costs." Additional papers were identified through the reference lists of collected studies. Little empirical academic research exists regarding the economic costs of nitrate contamination to community water systems. Accordingly, we reviewed available academic studies as well as reports from governmental and private entities to gain a preliminary understanding of these costs. Finally, previous work by outside contributors identified a significant number of studies included in this review.

THE CURRENT MAXIMUM CONTAMINANT LEVEL FOR NITRATE AND INFANT METHEMOGLOBINEMIA

The EPA set the maximum contaminant level for nitrate as nitrogen (N) in drinking water at 10 mg/L in 1962 to address a key health concern caused by nitrate contamination: infant methemoglobinemia (blue baby syndrome) (Anton et al., 1988). The EPA subsequently worked with states to enforce this contaminant limit on all public water systems. California's own limit of 45 mg/L of nitrate (NO3-) in drinking water is equivalent to the federal limit of 10 mg/L nitrate-N.

Infant methemoglobinemia results from the presence of methemoglobin, which prevents proper transportation of oxygen in the blood (Walton, 1951). Methemoglobin is formed when nitrosamines react with hemoglobin, altering the ferrous (Fe2+) state of iron found in blood to the ferric (Fe3+) state. Methemoglobin cannot bind oxygen, ultimately resulting in poor oxygenation and the symptoms of infant methemoglobinemia which include cyanosis, headaches, rapid heartbeat, nausea, and loss of consciousness. A key cause of this condition is the consumption of water containing high levels of nitrate. This was first reported in 1945 by Dr. Hunter H. Comley, who described two cases of infant methemoglobinemia (Comly, 1987). Both cases were located in Iowa, with the wells situated near "barnyards and pit privies" (Comly, 1987). Subsequent reviews on the conditions have confirmed the association.

In 1951, Dr. Graham Walton compiled a literature review on infant methemoglobinemia to form the basis for the limit on nitrate in drinking water (Walton, 1951). The review at that time found that the compiled data from 48 states identified 278 cases and 39 deaths correlating to nitrate content in the drinking water. There were no cases of methemoglobinemia among breastfed infants or among infants who ingested water containing less than 10 mg/L of nitrate, providing a clear, appropriate limit to address this issue.

While methemoglobinemia is not currently on California's list of reportable diseases (California Department of Public Health [CDPH], 2025), preliminary findings suggest that cyanotic attacks in infants are elevated in areas of California with high drinking water nitrate. In a public comment letter to the State Water Resources Control Board, Stanford researchers included preliminary findings from a study on blue baby syndrome in the Central Valley region of California that identified cases using Medi-Cal data (Hervey et al., 2024). They found that the area had a high number of domestic wells with elevated nitrate levels and cases of cyanotic attacks in infants, which can be indicative of blue baby syndrome. The study referenced dairy operations' contribution to nitrate levels through manure rather than synthetic fertilizer. Other literature (Fossen Johnson, 2019; Ward et al., 2018) reports that no new cases of infant methemoglobinemia have been formally reported in the United States, although such cases continue to be reported in other countries.

Approximately 92,000 households in the Central Valley rely on water from domestic wells, coinciding with elevated case counts of cyanotic attacks. While public water systems require regular testing, whether to test private domestic wells is often left to the owner's discretion. The EPA recommends water testing for private domestic wells, but it is not required by any federal regulation and is only regulated in certain regions of California. For example, the Central Coast and Central Valley Regional Water Quality Control Boards require testing of on-farm domestic and irrigation wells annually for certain owners of commercial irrigated lands in each region (California Regional Water Quality Control Board Central Coast Region [Central Coast Water Board], 2021; California Regional Water Quality Control Board Central Valley Region [Central Valley Water Board] 2012). Additionally, the California State Legislature recently enacted a law requiring domestic well owners to test wells that serve rental properties. However, this law applies only to rental properties located within the boundaries of a free testing program that has sufficient capacity (California Health and Safety Code § 116688, 2025). Testing of private domestic wells remains limited and insufficient. The sole scientific basis for the EPA's limit of 10 mg/L of nitrate in drinking water came from findings of methemoglobinemia in infants. Those findings did not assess additional health impacts of chronic exposure to nitrate in drinking water. However, this review will include additional evidence that shows a detrimental health impact from chronic exposure to levels below the current MCL, highlighting the need to redress current water quality concerns with renewed urgency.

HEALTH IMPACTS OF NITRATE CONTAMINATION IN DRINKING WATER

While the EPA's current maximum contaminant level for nitrate was meant to address acute toxicity in babies, an expanding body of research has demonstrated nitrate's potential to contribute to chronic diseases in adults at levels far below the MCL. Chronic exposure to drinking water with high levels of nitrate can be associated with various adverse health outcomes. The three most prevalent are cancer risk, thyroid disease, and birth complications.

Cancer Risk

Nitrate and nitrite intake are key drivers of endogenous formation of NOCs, which the World Health Organization (WHO) has classified as probable human carcinogens (WHO, 2019). Studies investigating the links between nitrate in drinking water and different forms of cancer have focused primarily on colorectal, bladder, ovarian, and renal cell carcinomas.

- *Colorectal Cancer:* A nationwide Danish cohort study found increased colorectal cancer risk at nitrate levels below the U.S. MCL of 10 mg/L (Schullehner et al., 2018). A statistically significant risk was found at drinking water levels above 3.86 mg/L. A country-wide study in New Zealand examined the association between exposure to nitrate-nitrogen and colorectal cancer rates (Richards et al., 2022). They estimated an average nitrate-nitrogen exposure rate of 0.49 mg/L for residents served by public water systems and 2.76 mg/L for residents using private wells, both well below the New Zealand legal limit of 11.3 mg/L nitrate-nitrogen. In California, researchers looked at 56,631 diagnoses of colorectal cancer and applied a generalized linear model to understand the impact of chronic and increasing nitrate exposure on the risk of colorectal cancer (Cisneros et al., 2025). They found a positive association between a 1 mg/L increase in nitrate concentration across exposure times of 1, 5, 10, 15, and 20 years. They also found that Hispanic, Black, and other identity categories had higher risk ratios than White individuals.
- *Bladder Cancer:* A study of postmenopausal women in Iowa found significant associations between nitrate intake and bladder cancer among women exposed to drinking water with over 5 mg/L nitrate for more than 4 years, compared with 0 years of comparable exposure (Jones et al., 2016). Elevated risk was observed only in cases with the most prolonged exposure (over 20 years) and the highest nitrate levels (9.5 mg/L). By contrast, a hospital-based case-control study in Spain found that bladder cancer risk was inconsistently associated with nitrate levels in drinking water below the regulatory limit (Espejo-Herrera et al., 2015). The EU nitrate limit is set at 50 mg/l of nitrate (NO3-), which is roughly equivalent to the US federal limit. Zeegers et al. (2006) found no association in the Netherlands, where average nitrate levels were only 1.68 mg/L.
- *Ovarian Cancer:* Inoue-Choi et al. (2015) documented a strong association between nitrate exposure and ovarian cancer risk. Risk was higher among those exposed to drinking water nitrate levels higher than 2.98 mg/L and private well users.

A population-based case-control study of renal cell carcinoma in Iowa studied subjects' drinking water and dietary intake and found no association with drinking water ingestion at >5 mg/L or >10 mg/L (Ward et al., 2007). However, the study excluded Des Moines residents, who were a large proportion of those with the highest exposure to elevated nitrate levels in drinking water.

These studies took place across a variety of locations with various population sizes and demographics. While the findings were mixed, the conclusions of multiple papers called for additional consideration of chronic exposure to nitrate at levels well below the regulatory limit. This underscores the necessity of quickly reducing or mitigating drinking water contamination for populations that are regularly exposed to elevated nitrate levels.

Thyroid Disease

Iodide is a necessary nutrient for the proper functioning of the thyroid gland, which can impact energy levels, metabolism, and essential body functions. Nitrate can inhibit iodide uptake from food, potentially affecting thyroid hormone production in individuals exposed to high nitrate levels in their drinking water. Disruption of proper thyroid hormone production can lead to fatigue, weight gain, rapid heart rate, or other symptoms of hypothyroidism or hyperthyroidism.

Consuming water with high nitrate levels can contribute to hypothyroidism. Tajtáková et al. (2006) conducted a study in areas where shallow well concentrations of nitrate were between 51-274 mg/L, measured as NO-3, or 11.5-61.9 mg/L, measured as N. The team found that Slovakian children drinking water with this range of high nitrate concentrations exhibited increased production of thyroid hormones and higher rates of subclinical hypothyroidism. The study's potential hypotheses regarding the effects of long-term nitrate exposure on thyroid health can be attributed to elevated nitrate intake from both drinking water and local food products. The researchers proposed that irrigating locally grown produce with water high in nitrate results in higher nitrate levels in the food itself, but did not find conclusive data in their findings to support this specific hypothesis.

Ward et al. (2007) identified elevated thyroid cancer risk after at least four years of exposure to nitrate levels in drinking water greater than 5 mg/L, but not associated with prevalence of hypothyroidism or hyperthyroidism. Studies on the impact of nitrate on thyroid health add to the evidence that makes clear the importance of addressing nitrate contamination with urgency.

Birth Complications

A study in Iowa and Texas found that mothers with daily ingestion of drinking water with 5 mg/L or higher were 2 times more likely to deliver babies with spina bifida (Brender et al., 2013). Spina bifida is a type of neural tube defect that occurs when the neural tube fails to close properly, resulting in a gap in the backbone. Mothers of babies born with limb deficiency, cleft palate, and cleft lip were 1.8, 1.9, and 1.8 times more likely to have consumed water with nitrate levels of 5.42 mg/L or higher. The study concluded that higher nitrate intake from public drinking water supplies was associated with several birth defects. A study in the agricultural region of Kings County, Nova Scotia, Canada, found a significant positive association between drinking-water nitrate levels of 1–5.56 mg/L and congenital anomalies, compared with those exposed to less than 1 mg/L (Holtby et al., 2014). This study considered both private wells and six public water systems.

The lack of data from private well users, who are at the greatest risk of high nitrate intake, complicates the available research on the topic. A review of the available literature on nitrate contamination and maternal health by Manassaram et al. (2007) found the evidence of a link between nitrate and adverse reproductive effects to be limited. Nevertheless, the review identified some cases linking birth defects to nitrate levels and highlights the importance of more extensive domestic well testing and data availability.

A key theme across epidemiologic studies is the importance of exposure duration. The strongest cancer associations tend to occur with multi-year exposures. Some studies (Inoue-Choi et al., 2015; Ward et al., 2007) illustrate how additional lifestyle factors, such as dietary vitamin C levels, can further compound the effects of nitrate contamination in drinking water. This highlights the importance of understanding nitrate contamination as one of the multiple environmental factors that can contribute to harmful outcomes. Studies on thyroid outcomes support the biological plausibility of nitrate-induced inhibition of iodide uptake. Neonatal health impacts were observed at concentrations as low as 1–2 mg/L and across varied study designs. The review of dermal exposure pathways confirms that oral ingestion remains the primary route of concern, indicating that regulatory efforts should prioritize drinking water treatment and source protection over bathing-water interventions. The one exception may be the risk of swallowing water during bathing. Still, given the small amount of water potentially consumed in that scenario, this would mostly pose a risk for infants under six months who are bathed by an adult and assumed to be under constant supervision.

DERMAL EXPOSURE RISK

Dermal absorption of nitrate has been studied less extensively than oral intake/exposure, but recent studies assessing the risk conclude that dermal exposure contributes minimally to nitrate-related health risks (Cocca et al., 2024). In a survey conducted in Northern Italy, a region with high nitrate contamination, researchers assessed the carcinogenic risk via dermal and oral pathways. They found that dermal exposure made a negligible contribution compared to oral exposure. As part of a multi-modal study on the contamination mechanisms, toxicity, and health risks of hardness, sulfate, and nitrate in public water sources, a nitrate health risk assessment found that total water intake can pose a chronic health risk in areas with high nitrate levels. Still, any impact specifically attributed to dermal absorption was negligible (Egbueri, 2023). Oral ingestion remains the predominant exposure route of concern. While studies don’t isolate the consumption of nitrate-high water via cooking in comparison to drinking, public health guides do recommend using bottled water as a safe alternative for food preparation where water is contaminated with nitrate (CDPH, 2014; Self and Waskom, 2025).

A cumulative risk framework underscores that communities rarely face nitrate contamination in isolation; nitrate frequently co-occurs with pesticides, heavy metals, and disinfection byproducts, amplifying overall health risk. Dermal exposure remains relevant in cumulative risk assessments, particularly when evaluating co-contaminants. While this review focuses on the health effects of nitrate in drinking water, it is important to recognize nitrate’s relationship to other environmental contaminants, which may interact to influence overall health risks in rural populations.

INCREASING EXPOSURE THROUGH FOOD INGESTION

About 80% of the dietary nitrate that we consume comes from the vegetables that we eat, with the highest nitrate concentrations found in leafy greens (Hord et al., 2009; Dodocioiu et al., 2025). Once ingested, nitrate in any food can be converted to nitrite through bacterial or enzymatic digestion (Choi et al., 2007). Nitrite can then be converted to nitrosamine or other NOCs, which may disrupt DNA and cause cancerous mutations. However, vegetables and fruits have many vitamins and antioxidant compounds that inhibit nitrosamine formation (Ward et al., 2018). In contrast, processed meats and drinking water lack these inhibiting compounds to balance out the nitrate conversion. This means nitrate consumed in processed meat or contaminated drinking water may pose a higher health and potentially carcinogenic risk than nitrates consumed from vegetables and fruits. This combination is particularly concerning for individuals whose domestic drinking water contains nitrate that exceeds the federal standard. The California Nitrogen Assessment explains that 50-70% of their nitrate consumption comes from drinking water (Tomich et al., 2016). A separate small-scale Iowa study found that subjects exposed to nitrate levels at or above the MCL could attribute 26-72% of their nitrate intake to drinking water. Individuals who consume water with high levels of nitrate are more vulnerable to the associated risks.

While there is a correlation between nitrate application to soil and nitrate concentration in crops, the impact of that nitrate is offset by the crops' antioxidants. Plants will bioaccumulate nitrate when it is available, namely when nitrogen fertilizer is applied, incorporating it into their leaves and fruiting body tissue (Liu et al., 2014). Since nitrogen often increases the yield and weight of crops (Yousefi & Karimi, 2023), and agricultural soils are often nitrogen-depleted due to repeated planting and nutrient uptake, farmers apply nitrogen fertilizer copiously. Research indicates that while many vegetables and fruits farmed with nitrogen fertilizer contain higher nitrate levels proportionate to the amount of nitrogen fertilizer applied, these crops do not pose a significant cancer risk given their incorporated nitrosamine inhibitors (Liu et al., 2014; Wang & Li, 2004; Hosseini et al., 2021).

EXPOSURE THROUGH NON-DRINKING HOUSEHOLD USE

There are myriad household uses of water beyond drinking—such as cooking, bathing, dishwashing, tooth brushing, and gardening—that may pose health risks when the water supply is contaminated with nitrate (Tajtáková et al., 2006). Cooking represents a significant and often overlooked exposure pathway because it can lead to direct ingestion of contaminated water, yet there is very little peer-reviewed research on the topic. Rajabi et al. (2025) conducted a study that found that boiling nitrate-contaminated water raises the concentration of nitrate in the water, due to the concentrating effect of evaporation. This research contradicts the common misconception that boiling water removes all contaminants. In reality, boiling is only effective at removing bacteria, viruses, and protozoa (EPA, 2017). Boiling nitrate-contaminated water only increases its nitrate concentration and thereby the water's potential toxicity to the consumer (Rajabi et al., 2025). Preparing and consuming contaminated water—through foods such as soup, porridge, beans, coffee, and stew—may even pose a higher risk to the consumer than drinking water, due to the relative proportion of nitrate incorporated into the meal through boiling. Although more research is necessary, cooking and other household uses for water should be considered potential health risks for families reliant on nitrate-contaminated tap water. While studies do not isolate the consumption of high nitrate water via cooking in comparison to drinking, public health guides do recommend using bottled water as a safe alternative for food preparation where water is contaminated with nitrate (CDPH, 2014; Self and Waskom, 2025).

COST OF NITRATE CONTAMINATION

The link between chronic nitrate exposure and adverse health outcomes has been demonstrated in the literature over the past few decades. Beyond blue baby syndrome, nitrate exposure at legally acceptable levels in drinking water is affecting the health of individuals of all ages. Cancer risk, birth complications, and thyroid disease are the most prevalent in the epidemiological literature associated with nitrate exposure and health. Several studies also focus on the associated costs of nitrate exposure, including medical care costs, lost productivity due to poor health, adaptation costs for communities with known contamination levels, and potential costs for cleaning and treating the pollution. The following section details some of the many additional costs of nitrate contamination. As elaborated below, further delays in reducing nitrate contamination accrue costs across many other sectors.

Medical Care Cost

A study focusing on the costs of colorectal cancer, the fourth most prevalent cancer in the United States, and adverse pregnancy outcomes attributable to nitrate contamination within the United States found that cancer-related medical costs due to nitrate exposure alone can be estimated at $250 million to $1.5 billion per year (Temkin et al., 2019). The cost increases when indirect costs from productivity losses are considered, estimated here at $1.3-6.5 billion annually. A more limited study focusing on the state of Wisconsin similarly estimated the nitrate-attributable costs of adverse health outcomes (Mathewson et al., 2020). Researchers estimated the number of colorectal, ovarian, thyroid, and bladder cancer cases to range annually from 111 to 298. The study attributed 137-149 cases of very low birth weight, 72–79 cases of very preterm birth, and two cases of neural tube defects to exposure to nitrate-contaminated drinking water. Using a similar methodology to Temkin et al. (2019), they found that the direct medical costs for these health outcomes ranged from $23 to $80 million annually for the state.

Adaptation Cost: Bottled Water

Adaptation costs occur when households are forced to seek alternative sources to meet their drinking water needs. This usually happens through purchasing bottled water, which is the only safe water source available to households that experience water quality issues. Moore et al. (2011)

found that households in California's San Joaquin Valley, a region heavily affected by agricultural nitrate contamination, spent an average of 4.1% of household income on drinking water, primarily due to reliance on bottled water and home treatment. This is more than double the EPA-recommended 1.5% affordability benchmarks and reflects broader environmental justice disparities. In the Beverley Grand community water system, the survey found that 81% of households drink exclusively from non-tap water sources, even though 43% still cook with that same water.

A study in Northern California, matching recorded water violations with supermarket sales data, aimed to estimate the impact on expenses associated with drinking water contamination (Zivin et al., 2011). It found that, in the studied population, although not statistically significant from zero, spending on bottled water increased by 26% during nitrate contamination advisories. Researchers used this information to estimate that U.S. residents spend $1.77 million per year in response to nitrate exceedances. This estimate is limited to water bottle sales, which is only one of the various adaptation costs that people incur in cases of contamination.

Clean-Up Cost

In a study on Denmark's drinking water, researchers used the value of a life year (VOLY) and the societal costs of cancer, as determined in a report by the Danish Center for Health Economics, to first calculate the annual cost of nitrate-attributable colorectal cancer cases in the country (Jacobsen et al., 2024). They then determined the costs of reducing nitrate content in drinking water by lowering the regulatory limit. They found that 7% of water suppliers would not meet the new standard of 9.25 mg/L, and 10% would fail the even stricter standard of 3.87 mg/L. To estimate the costs of meeting these limits, they considered changes in land use management, reallocation of wells, and water treatment. Land use management included environmental regulations that protected groundwater reservoirs through set-aside zones and restrictions on nitrogen use in agriculture. In the results, the team found that in both scenarios the benefits outweighed the costs. Lowering the limit to 9.25 mg/L would result in 72 fewer cases of colorectal cancer and avoided health costs would amount to $179 million. For the 3.87 mg/L scenario, an additional 55 cases would be avoided, and an extra $138 million per year would be saved. The costs associated with these two scenarios are estimated to be $0.03–1.84 per mg. For Denmark, with its current nitrate levels in public drinking water systems, this would result in total costs of $9 million and $6 million per year for the two scenarios to reduce nitrate contamination, with potential health-related savings of $179 million and $138 million respectively. In other words, the short-term costs of reducing exposure to nitrates can help countries avoid substantial health costs in the long-term.

In a study of public drinking water systems in the United States, California and Ohio had the highest average number of people served by systems in violation of nitrate contamination: 139,149 and 278,374, respectively (Pennino et al., 2017). This excludes private wells, for which a study of

200 wells in the Central Valley found that 44% of the samples did not meet legal requirements (Lockhart et al., 2013), and this is likely an underestimate given that the Central Valley has anywhere between 100,000-150,000 domestic wells (Harter et al., 2012).

Cradock et al. (2024) found the costs necessary to serve families with young children, highlighting an average annual cost of $73,000 to monitor and treat nitrate in homes of families with children ages 0-5 years. The study was designed to better understand the costs of various ongoing strategies that ensure safe drinking water for families with young children in the Northeast, Midwest, and Western regions of the United States. The goal of this study was to inform policy decisions that could impact the health of young children exposed to drinking water contaminated by lead, arsenic, and nitrates. The selected strategies included four private well water testing programs, a lead service line replacement program, a point of use filtration system, and a filter pitcher distribution program. In Porterville, California, the study found that the total annual average cost to monitor and treat nitrate for homes of families with young children 0-5 years is $73,000.

Keeler and Polasky (2014) estimated that addressing wells exceeding 10 mg/L in Southeastern Minnesota (11 counties) over a 20-year period would result in total costs of $1.4–$4.8 million. They studied the costs of remediation actions to improve groundwater nitrate levels, including replacing contaminated wells, installing filtration systems, and water treatment, as well as the avoidance costs associated with water contamination, such as bottled water for cooking and drinking. The cost per well over a 20-year time horizon is estimated at $2,600–$6,710 for nitrate treatment and $7,200–$16,000 for new wells. Water treatment technologies such as ion exchange and reverse osmosis remain costly for both utilities and households.

Cost to Community Water System Owners and Ratepayers

The costs of nitrate contamination to community water system owners and operators and ratepayers deserve special attention—as ratepayers often shoulder the cost of addressing nitrate contamination. California law defines a community water system as a public water system that serves at least 15 service connections used by yearlong residents or regularly serves at least 25 yearlong residents of the area served by the system (Cal. Health & Safety Code § 116275). Community water systems typically address nitrate exceedances by replacing the water system's well and/or by installing treatment technology (Volzer et al., 2025).

Community water systems may address nitrate contamination depending on their size. Larger community water systems can diffuse high concentrations of nitrate contamination by sourcing water from multiple wells or by spreading the cost among a larger pool of ratepayers. However, smaller water systems operate at higher per unit costs to deliver drinking water to small, often rural communities. Their smaller ratepayer base prevents them from having the funding, infrastructure, or management capacity necessary to construct and maintain multi-million-dollar nitrate treatment systems (Canada et al., 2012). Cheaper alternatives like drilling new wells or blending the contaminated water with other sources may also not be feasible for smaller water systems because of fluctuating and increasing groundwater nitrate levels and because there may not be a source with which to blend (Moore et al., 2011).

The following examples are illustrative of how smaller community water systems in California face increasing cost challenges related to nitrate contamination. For instance, in San Lucas, an unincorporated community in Monterey County with approximately 300 residents, when the community's water source tested above the 10 mg/L MCL for nitrate, the local water district drilled a new well to provide drinking water (Amec Foster Wheeler Environment & Infrastructure, Inc. & SRT Engineers, 2015; Yates et al., 2011). It is unclear whether public funds covered any well monitoring or a new transmission line, but a government report reveals that the party responsible for nitrate exceedances in the area funded at least a portion of acquiring land and drilling the replacement well (Mission Ranches Company LLC. & Naraghi Family, 2013). When the new well also tested above the MCL for nitrate, both Monterey County and the State Water Resources Control Board proposed nitrate treatment projects ranging from $10 million to nearly $30 million dollars for the community (MKN & Associates, Inc., 2025). In Grayson, an unincorporated community in Stanislaus County with approximately 1,100 residents, the city installed a nitrate treatment system after being incorporated into the City of Modesto's water system. The estimated cost for this nitrate treatment system was $800-900 per acre-foot and it operates at a price of around $240,000 annually (Moore et al., 2011).

Previous literature also indicates the high costs of nitrate treatment systems to community water systems. In a 2012 study on nitrate treatment costs for private domestic wells and local small water systems servicing 34,000 rural residents in the Tulare Lake Basin and Salinas Valley, researchers estimated nitrate treatment options to cost $2.5 million, translating to $80 to $142 per year for each affected individual (Harter et al., 2012).

Larger water systems, such as municipalities, also face high costs to address nitrate contamination. The nitrate levels in many incorporated areas in the Salinas and San Joaquin Valleys test at elevated levels for nitrate (City of Gonzales, 2025; City of Greenfield, 2025; City of King City, 2025; City of Madera, 2025; City of Modesto, 2025; City of Salinas, 2025; City of Tulare, 2025; City of Visalia, 2025). In Fresno, the water system, which provides water to the over half-million residents, regularly tests at nitrate levels near or above the MCL (City of Fresno Water Division, 2021, 2022, 2023, 2024, 2025). And Cal Water-Salinas, serving over 100,000 residents, has had to treat their water supply with ion exchange treatments to address nitrate contamination (Central Coast Water Board, 2021). A 1995 staff report from the State Water Resources Control Board mentioned that all cities in the Salinas Valley had to replace their drinking water wells due to high nitrate contamination (Greater Monterey County Integrated Regional Water Management Program, 2017). Further, water systems located in the Tulare Lake Basin and Salinas Valley regions requested more state funding to address nitrate contamination compared to water systems located in the rest of the state—at $29 per person verses the statewide average of $5 per person.

This was also reflected in 9% of the requested funding in these regions being applied to drinking water nitrate projects compared to 1.6% in the rest of the state (Canada et al., 2012).

In 2025, the Central Coast Regional Water Quality Control Board (Central Coast Water Board) completed an assessment on both the extent of, as well as cost of, providing interim alternative water supplies to communities and residents whose drinking water exceeds the nitrate MCL because of agricultural discharges (Central Coast Water Board, 2025). The Central Coast Water Board estimated that 17 public water systems, 117 state small water systems, and 3,005 domestic wells exceed the MCL for nitrate due to agricultural activities. This means that, within the Central Coast Region, approximately 14,039 people are impacted by nitrate contamination. In total, the Central Coast Water Board estimated that interim alternative water supplies would cost an average of $6.4 to $7.2 million per year, over a 10-year period. Interim alternative water supplies include bottled water, point of use, and point of entry treatment systems.

Because community water systems, both small and large, must address nitrate contamination, these water systems inevitably pass along those costs to their ratepayers. Nitrate treatment, well closures, or new well construction increase costs for the water supplier. And the water supplier passes these costs to the consumer through higher water rates (California State Water Resources Control Board, 2013; Volzer et al., 2025).

ENVIRONMENTAL JUSTICE CONSIDERATIONS

It is important to note that both the health and socioeconomic costs associated with nitrate contamination are not equitably distributed. In the San Joaquin Valley, Balazs et al. (2011) found that community water systems (CWS), defined as public water systems that serve water to at least 25 people or have more than 15 service connections, that served a larger percentage of Latino households had higher nitrate levels. Subsequent studies on CWS provide further evidence of this ethnic disparity on the state level. For example, Pace et al. (2022) found a 10% increase in the Latinx population in a CWS was associated with a 21% increase in likelihood of elevated nitrate. Additionally, Sum (2024) found that CWS that serve majority-Latino populations exhibit persistently higher and more variable drinking water nitrate concentrations. Nitrate contamination disparities are not limited to disparities based on ethnicity. Elevated nitrate concentrations have also been observed in CWS serving higher proportions of renter households (Balazs et al., 2011) as well as non-Latinx communities of color (Pace et al., 2022). This indicates that various racial, ethnic, and socioeconomic factors are all associated with nitrate-contaminated drinking water in California.

Geographically, exposure is concentrated in agricultural regions where agricultural nitrate application contributes to elevated nitrate levels in groundwater (Harter et al., 2012; Balazs et al., 2011). In the Tulare Lake Basin and Salinas Valley, 2.6 million people, or roughly 97% of the population, depend on groundwater for drinking water. Approximately 254,000 residents in these basins rely on groundwater that may exceed the drinking water standard for nitrate. Continued basin-wide trends in nitrate groundwater concentration may increase the affected population to nearly 80% by 2050 (Harter et al., 2012). In the San Joaquin Valley, 95% of the population relies on the groundwater for drinking water (Balazs et al., 2011). Further evidence indicates that geographic and sociodemographic factors can interact to exacerbate exposure. Pace et al. (2022) found that the proportion of people of color and renter households exposed to nitrate above the MCL was higher in the San Joaquin Valley, Imperial Valley, and Central Coast. These regions encompass nine of the most agriculturally productive counties in the United States (California Department of Food and Agriculture, 2024).

Empirical evidence indicates that disadvantaged communities are disproportionately served by water systems that fail to meet drinking water standards; in 2021, more than two-thirds of noncompliant systems were in disadvantaged communities (DACs) with significant financial need (California State Auditor, 2022). A disadvantaged community is defined as a community with an annual median household income that is less than 80 percent of the statewide annual median household income, and one that is overburdened by pollution and health challenges (Cal. Water Code § 79505.5; Aiken et al., 2023). As previously noted, water-related expenses already constitute a nontrivial share of household income in low-income communities, suggesting that additional adaptation costs weigh disproportionately on low-income residents.

These patterns of unequal nitrate exposure are associated with increased adaptation costs at the household level. As discussed above, Latino, low-income, and rural populations are disproportionately exposed to elevated nitrate concentrations in drinking water. In contexts where community water systems do not consistently provide water that meets regulatory requirements, households often adapt to secure potable water, including purchasing bottled water or point-of-use treatment technologies. As a result, populations experiencing higher levels of exposure are also more likely to incur the costs associated with mitigating that exposure (Moore et al., 2011).

Disparities are further amplified among domestic well users, whose wells are often not subject to mandatory testing or routine monitoring. Domestic wells are concentrated in rural, agricultural, and socioeconomically disadvantaged areas; approximately 48 percent of domestic well users in the Central Valley live within DACs. These wells are generally drilled to a shallower depth, making them more susceptible to nitrate contamination compared to community water systems (Aiken et al., 2023). Consistent with community water systems socioeconomic trends, nitrate and other drinking water contaminants are most pronounced in domestic wells serving communities of color (Pace et al. 2022).

The unequal distribution of nitrate contamination has measurable health consequences: Tariqi and Naughton (2021) found that half of the Central Valley's area contained DACs, which had twice the rate of thyroid cancer and higher numbers of nitrate contaminated wells and hotspots compared to the state average. Together, these findings indicate that nitrate exposure, adaption costs, and associated health risks are disproportionately concentrated among low-income, rural and Latino populations, where groundwater dependence and limited financial resources further exacerbate the economic and health burdens associated with nitrate contamination.

DISCUSSION

The literature reviewed highlights the ongoing challenges posed by elevated nitrate levels in drinking water, primarily driven by agricultural production. Current nitrate regulation has not yet ensured legally safe drinking water for all; many communities continue to experience nitrate levels above the 10 mg/L MCL, and evidence indicates that these challenges are likely to intensify. Nitrate concentrations in global water supplies are projected to rise due to increasing nitrogen fertilizer use and the growing concentration of animal manure (Ward et al., 2018). In the Salinas Valley and Tulare lake basin, trends suggest that the proportion of the population exposed to elevated nitrate in groundwater could reach nearly 80% by 2050 (Harter et al., 2012). Researchers are studying rural communities around the world to better understand how increased nitrate leaching into sources of drinking water affects community members' health.

The current MCL, set by the EPA and followed by state regulations, was based solely on cases of infant methemoglobinemia (Anton et al., 1988). While most literature (Fossen Johnson 2019; Ward et al., 2018) reports that cases have decreased significantly, evidence suggests this may still be an issue in rural communities across California's major agricultural regions (Hervey et al., 2024). Further, the decrease in cases of infant methemoglobinemia could be due to changes in reporting such cases.

Existing regulations do not adequately protect private well users, although there are exceptions in some areas of the state. The Central Valley Salinity Alternatives for Long-term Sustainability (CV-SALTS) is an initiative started in 2006 as a collaborative effort across state and federal agencies, industry partners, and environmental justice and water advocacy groups. The goal expanded beyond salinity issues and now includes a Nitrate Control Program that provides water-quality testing for residential wells in parts of the Central Valley. A study by Santa Clara University examined the impact of CV-SALTS in the Modesto and Turlock Priority 1 Management Zones, which are areas within the priority watershed basins in the Central Valley that are defined and legally required for permittees to provide safe drinking water (Lei et al., n.d.). The study used surveys with over 100 residents and a comparative analysis of the Early Action Plan Reports for all Priority 1 basins. The results found that the program is underperforming against its projected timeline, that relief efforts to provide bottled water to households with low water quality are insufficient to address the need, and that source reduction and monitoring are not prioritized enough to identify and address issues in a timely manner. Central Valley residents reliant on private wells still need additional support and resources to address contamination issues and receive equitable water access.

Evidence collected in this review demonstrates associations between chronic ingestion of nitrate below the maximum limit and various adverse health outcomes, including cancer risk (Schullehner et al., 2018; Jones et al., 2016; Inoue-Choi et al., 2015; Ward et al., 2007), thyroid disorders (Ward et al., 2007), and neonatal complications (Brender et al., 2013; Holtby et al., 2014). While some cancer studies report null findings or population differences, the consistency of positive associations at even 2–6 mg/L highlights the need for further research.

The economic literature highlights issues of inequity and social costs relevant to policy design. Most studies estimating the medical costs associated with nitrate-attributable conditions focused on cancer and adverse birth outcomes, finding that costs may reach billions of dollars annually in the United States. Additionally, household costs associated with bottled water, home water filtration, and other adaptation methods to address contamination disproportionately burden rural, low-income, and agricultural communities (Aiken et al., 2023; Harter et al., 2012; Moore et al., 2011).

Agricultural producers, whose activities are the dominant source of nitrate loading across California, do not directly incur the costs of nitrate contamination (Harter et al., 2012). Groundwater nitrate contamination is a classic example of nonpoint source pollution, making regulatory enforcement politically challenging and often shifting the cost of treatment and health impacts onto consumers, ratepayers, and public agencies. Fertilizer runoff contaminating groundwater and affecting both public and domestic well users incurs a range of costs, including the need for regular testing, treatment costs, bottled water expenses, and ultimately medical costs. Several recent cost–benefit analyses, however, demonstrate that lowering nitrate limits—while expensive in some contexts—yields net societal benefits when avoided health outcomes and the costs of lowering regulatory limits are monetized (Jacobsen et al., 2024; Mathewson et al., 2020).

Overall, the literature indicates the significant risks communities face at various levels of nitrate contamination and makes a clear case for the importance of establishing regulatory standards to potentially reduce and mitigate that risk.

CONCLUSION

Nitrate contamination remains a widespread and persistent challenge for drinking water in the United States, particularly in California. A growing body of evidence indicates that chronic exposure at levels below the current standard pose meaningful health risks including cancer (Schullehner et al., 2018; Jones et al., 2016; Inoue-Choi et al., 2015; Ward et al., 2007), thyroid disorders (Ward et al., 2007), and neonatal complications (Brender et al., 2013; Holtby et al., 2014). While some cancer studies report null findings or population differences, the consistency of positive associations even at 2–6 mg/L highlights the need for further research and urgent attention to meeting the most basic regulatory standards. Epidemiologic evidence supports increased regulatory scrutiny at concentrations in the 2–6 mg/L range. Health risks in nitrate-contaminated drinking water can be amplified through household uses, particularly cooking, which can concentrate nitrate through evaporation and further increase exposure.

Research further demonstrates that nitrate exposure is disproportionately concentrated in low-income, rural, and majority Latino communities, particularly in agricultural regions reliant on groundwater (Balazs et al., 2011; Pace et al., 2022; Sum, 2024). Structural factors including reliance on unregulated domestic wells (Aiken, 2023; Pace et al., 2022) and proximity to contamination sources can contribute to these inequalities (Balazs et al., 2011). These disadvantaged communities face a greater economic burden, paying a higher share of their income towards safe drinking water alternatives (Harter et al., 2012; Moore et al., 2011). Elevated nitrate exposure in these communities is associated with measurable health disparities, with a study finding increased rates of thyroid cancer in disadvantaged communities with nitrate contaminated drinking water sources (Tariqi and Naughton, 2021). Collectively, these findings indicate that low-income, rural and Latino populations are disproportionately exposed to nitrate contaminated groundwater and, as a result, bear a disproportionate share of the associated economic costs and adverse health impacts.

The literature on the health and socioeconomic impacts of contamination makes clear that failing to control nitrate levels entails substantial personal and financial costs for households, states, and health systems. At the same time, improved private well testing and preventing increasing concentration levels can help reduce overall costs. Lower levels of nitrate contamination are associated with more positive health outcomes and can improve quality of life by ensuring safer drinking water for all.

Collectively, the evidence suggests the need to address nitrate contamination with urgency to protect human health and safety.

REFERENCES

Aiken, M. L., Pace, C. E., Ramachandran, M., Schwabe, K. A., Ajami, H., Link, B. G., & Ying, S. C. (2023). Disparities in drinking water manganese concentrations in domestic wells and community water systems in the Central Valley, CA, USA. *Environmental Science & Technology,* 57(5), 1987–1996. https://doi.org/10.1021/acs.est.2c08548

Amec Foster Wheeler Environment & Infrastructure, Inc., & SRT Engineers. (2015). *Final Feasibility Study: San Lucas County Water District Water Supply Project*. (Project No. IR13164650).

Anton, E. C., Barnickol, J. L., & Schnaible, D. R. (1988, October). *Nitrate in drinking water: Report to the Legislature* (Report No. 88-11WQ). State Water Resources Control Board.

Balazs, C., Morello-Frosch, R., Hubbard, A., & Ray, I. (2011). Social disparities in nitrate-contaminated drinking water in California's San Joaquin Valley. *Environmental health perspectives*, *119*(9), 1272–1278. https://doi.org/10.1289/ehp.1002878

Brender, J. D., Weyer, P. J., Romitti, P. A., Mohanty, B. P., Shinde, M. U., Vuong, A. M., Sharkey, J. R., Dwivedi, D., Horel, S. A., Kantamneni, J., Huber, J. C., Jr, Zheng, Q., Werler, M. M., Kelley, K. E., Griesenbeck, J. S., Zhan, F. B., Langlois, P. H., Suarez, L., Canfield, M. A., & National Birth Defects Prevention Study (2013). Prenatal nitrate intake from drinking water and selected birth defects in offspring of participants in the national birth defects prevention study. *Environmental health perspectives*, *121*(9), 1083–1089. https://doi.org/10.1289/ehp.1206249

California Department of Food and Agriculture. (2024, February 13). *Nine California counties make top-10 list for AG sales in the U.S.* CDFA’s Planting Seeds Blog. https://plantingseedsblog.cdfa.ca.gov/wordpress/index.php/2024/02/13/nine-california-counties-make-top-10-list-for-ag-sales-in-the-u-s/

California Department of Public Health. (2014, May) *Nitrate Fact Sheet.* www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/nitrate/fact_sheet_nitrate_may2014_update.pdf.

California Department of Public Health. (2025, June). *Reportable diseases and conditions*. https://www.cdph.ca.gov/Programs/CID/DCDC/CDPH%20Document%20Library/ReportableDiseases_June2025.pdf.

California Department of Water Resources. (2026, March 12). *Local agencies across California continue advancements toward groundwater sustainability.* https://water.ca.gov/News/News-Releases/2026/Mar-2026/Local-Agencies-Across-California-Continue-Advancements-Toward-Groundwater-Sustainability

California Health and Safety Code § 116688 (2025).

California Regional Water Quality Control Board, Central Coast Region. (2025). *Assessment of Interim Drinking Water Needs and Costs in Central Coast Areas Affected by Agricultural Nitrate Groundwater Contamination.* https://www.waterboards.ca.gov/centralcoast/water_issues/programs/ilp/docs/2025/assessment-of-interim-drinking-water-needs-and-costs.pdf.

California Regional Water Quality Control Board, Central Coast Region. (2021, April 15). *General Waste Discharge Requirements for Discharges from Irrigated Lands.* (Order No. R3-2021-0040, Attachment A).

California Regional Water Quality Control Board, Central Valley Region. (2012, December). *Waste discharge requirements general order for growers within the Eastern San Joaquin River Watershed that are members of a third-party group* (Order No. R5-2012-0116-11).

California State Auditor. (2022, July 26) *State Water Resources Control Board: It Lacks the Urgency Necessary to Ensure That Failing Water Systems Receive Needed Assistance in a Timely Manner*. (Report No. 2021-118). https://information.auditor.ca.gov/reports/2021-118/index.html

California State Water Resources Control Board. (2013). *Recommendations Addressing Nitrate in Groundwater: Report for the State Water Resources Control Board Report to the Legislature.* https://www.waterboards.ca.gov/water_issues/programs/nitrate_project/docs/nitrate_rpt.pdf

Canada, H.E., Harter, T., Honeycutt, K., Jessoe, K., Jenkins, M.W. & Lund, J.R. (2012). *Technical Report 8 in 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.* Center for Watershed Sciences, University of California, Davis. https://watershed.ucdavis.edu/sites/g/files/dgvnsk8531/files/products/2022-05/Regulatory%20and%20Funding%20Options.pdf

Choi S.Y., Chung M.J., Lee S.J., Shin J.H. &Sung N.J. (2007). N-nitrosamine inhibition by strawberry, garlic, kale, and the effects of nitrite-scavenging and N-nitrosamine formation by functional compounds in strawberry and garlic. *Food Control*, *18*(5), 485–491. https://www.sciencedirect.com/science/article/pii/S0956713506000090

Cisneros, R., Amiri, M., & Gharibi, H. (2025). The association between increases in nitrate in drinking water and colorectal cancer incidence rates in California, USA. *Cancer causes & control: CCC*, *36*(10), 1041–1057. https://doi.org/10.1007/s10552-025-02003-5

City of Fresno Water Division. (2025) *Water Quality Annual Report 2024.* Fresno City, https://www.fresno.gov/wp-content/uploads/2025/06/COF-Water-Quality-CCR-Report-ADA-062425_v5-10w783.pdf

City of Fresno Water Division. (2024) *Water Quality Annual Report 2023*. Fresno City, https://www.fresno.gov/wp-content/uploads/2024/06/CCR2023-10w41.pdf

City of Fresno Water Division. (2023) *Water Quality Annual Report 2022.* Fresno City, https://www.fresno.gov/wp-content/uploads/2023/06/CCR2022-2.pdf

City of Fresno Water Division. (2022) *Water Quality Annual Report 2021*. Fresno City, https://www.fresno.gov/wp-content/uploads/2023/06/CCR2021-ADA-English.pdf

City of Fresno Water Division. (2021) *Water Quality Annual Report 2020*. Fresno City, https://www.fresno.gov/wp-content/uploads/2023/06/CCR2020_Online.pdf

City of Gonzales. (2025). *Annual Water Quality Report 2024.* Gonzales City Hall, Gonzales. https://gonzalesca.gov/sites/default/files/2025-07/gonzalesccr2024.pdf

City of Greenfield. (2025). *2024 Consumer Confidence Report.* California State Water Resources Board, Consumer Confidence Report. https://www.greenfieldca.gov/DocumentCenter/View/4970/2024-City-of-Greenfield-CCR?bidId=

City of King City. (2025). *King City 2024 Water Quality Report.* California Water Service King City District, King City. https://www.calwater.com/ccrs/kc-kc-2024/

City of Madera. (2025). *City of Madera Water Quality Report 2024.* California State Water Resources Board, Consumer Confidence Report. https://ear.waterboards.ca.gov/Home/ViewCCRPwsID=CA2010002&Year=2024&isCert=false

City of Modesto. (2025). *2024 Water Quality Report Modesto System.* Modesto. https://www.modestogov.com/ArchiveCenter/ViewFile/Item/4544

City of Salinas. (2025). *Salinas System 2024 Water Quality Report*. California Water Service Salinas District, Salinas. https://www.calwater.com/ccrs/sln-sln-2024/

City of Tulare. (2025). *Annual Water Quality Report 2024.* Tulare. https://www.tulare.ca.gov/home/showdocument/23167

City of Visalia. (2025). *2024 Water Quality Report*. California Water Service Visalia District, Visalia. https://www.calwater.com/docs/ccr/2024/vis-vis-2024.pdf

Cocca, D., Lasagna, M., Destefanis, E., Bottasso, C., & De Luca, D. A. (2024). Human Health Risk Assessment of Heavy Metals and Nitrates Associated with Oral and Dermal Groundwater Exposure: The Poirino Plateau Case Study (NW Italy). *Sustainability*, *16*(1), 222. https://doi.org/10.3390/su16010222

Comly H. H. (1987). Landmark article Sept 8, 1945: Cyanosis in infants caused by nitrates in well-water. By Hunter H. Comly. *JAMA*, *257*(20), 2788–2792.

Cradock, A. L., Barrett, J. L., Nink, E., & Wilking, C. (2024) An Economic Evaluation of Strategies to Ensure Safer Drinking Water in the Homes of Families with Young Children in Select United States Locations. *Preventive Medicine Reports, 38,* 102588. https://doi.org/10.1016/j.pmedr.2024.102588

Dodocioiu, A. M., Buzatu, G.-D., & Botu, M. (2025). Nitrates and Nitrites in Vegetables and the Health Risk. *Foods*, *14*(17), 3037. https://doi.org/10.3390/foods14173037

Egbueri J. C. (2023). A multi-model study for understanding the contamination mechanisms, toxicity and health risks of hardness, sulfate, and nitrate in natural water resources. *Environmental science and pollution research international*, *30*(22), 61626–61658. https://doi.org/10.1007/s11356-023-26396-5

U.S. Environmental Protection Agency. (2017, September). *Emergency disinfection of drinking water* (EPA 816-F-15-003). https://www.epa.gov/sites/default/files/2017-09/documents/emergency_disinfection_of_drinking_water_sept2017.pdf

U.S. Environmental Protection Agency. (2025, December 1) *National Primary Drinking Water Regulations.* www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.

Espejo-Herrera, N., Cantor, K. P., Malats, N., Silverman, D. T., Tardón, A., García-Closas, R., Serra, C., Kogevinas, M., & Villanueva, C. M. (2015). Nitrate in drinking water and bladder cancer risk in Spain. *Environmental research*, *137*, 299–307. https://doi.org/10.1016/j.envres.2014.10.034

Greater Monterey County Integrated Regional Water Management Program. (2017). *Chapter 3: Identifying Drinking Water and Wastewater Problems.*

https://www.greatermontereyirwmp.org/wp-content/uploads/2017/11/Chapter-3-Identifying-Problems-smaller_11.08.17.pdf

Harter, T., Lund, J. R., Darby, J., Fogg, G. E., Howitt, R., Jessoe, K. K., Pettygrove, G. S., Quinn, J. F., Viers, J. H., Boyle, D. B., Canada, H. E., DeLaMora, N., Dzurella, K. N., Fryjoff-Hung, A., Hollander, A. D., Honeycutt, K. L., Jenkins, M. W., Jensen, V. B., King, A. M., Kourakos, G., Liptzin, D., Lopez, E. M., Mayzelle, M. M., McNally, A., Medellín-Azuara, J., & Rosenstock, T. S. (2012). *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). Center for Watershed Sciences, University of California, Davis.http://groundwaternitrate.ucdavis.edu https://watershed.ucdavis.edu/sites/g/files/dgvnsk8531/files/products/2022-05/Regulatory%20and%20Funding%20Options.pdf

Holtby, C. E., Guernsey, J. R., Allen, A. C., Vanleeuwen, J. A., Allen, V. M., & Gordon, R. J. (2014). A population-based case-control study of drinking-water nitrate and congenital anomalies using Geographic Information Systems (GIS) to develop individual-level exposure estimates. *International journal of environmental research and public health*, *11*(2), 1803–1823. https://doi.org/10.3390/ijerph110201803

Hosseini, F., Majdi, M., Naghshi, S., Sheikhhossein, F., Djafarian, K., & Shab-Bidar, S. (2021). Nitrate-nitrite exposure through drinking water and diet and risk of colorectal cancer: A systematic review and meta-analysis of observational studies. *Clinical Nutrition, 40*(5), 3073–3081.

Jones, R. R., Weyer, P. J., DellaValle, C. T., Inoue-Choi, M., Anderson, K. E., Cantor, K. P., Krasner, S., Robien, K., Freeman, L. E., Silverman, D. T., & Ward, M. H. (2016). Nitrate from Drinking Water and Diet and Bladder Cancer Among Postmenopausal Women in Iowa. *Environmental health perspectives*, *124*(11), 1751–1758. https://doi.org/10.1289/EHP191

Hervey, G., Sivas, D. A., Wara, M., Mastrandrea, M., Zerbe, A., & Jurenci, C. (2024, December 19). *Comments on Draft Dairy Order, SWRCB/OCC FILES A-2283(b)*. Stanford Woods Institute for the Environment.

Hord, N. G., Tang, Y., & Bryan, N. S. (2009). Food sources of nitrates and nitrites: The physiologic context for potential health benefits. *The American Journal of Clinical Nutrition, 90*(1), 1–10. https://doi.org/10.3945/ajcn.2008.27131

Inoue-Choi, M., Jones, R. R., Anderson, K. E., Cantor, K. P., Cerhan, J. R., Krasner, S., Robien, K., Weyer, P. J., & Ward, M. H. (2015). Nitrate and nitrite ingestion and risk of ovarian cancer among postmenopausal women in Iowa. *International journal of cancer*, *137*(1), 173–182. https://doi.org/10.1002/ijc.29365

Jacobsen, B. H., Hansen, B. and Schullehner, B. (2024). Health-Economic Valuation of Lowering Nitrate Standards in Drinking Water Related to Colorectal Cancer in Denmark. *The Science of the Total Environment, 90*, 167378.

Killpack, S. C., & Buchholz, D. (2022). *Nitrogen in the environment: Leaching (WQ262)*. University of Missouri Extension. https://extension.missouri.edu/publications/wq262

Keeler, B. L., and Polasky, S. (2014). Land-Use Change and Costs to Rural Households: A Case Study in Groundwater Nitrate Contamination. *Environmental Research Letters 9*(7), 74002–10.

Lei, S., Stewart-Frey, I., Dialesandro, J., & Jensen, N. (n.d.). *Evaluating the effectiveness of CV-SALTS*. Frugal Innovation Hub, Santa Clara University. www.scu.edu/engineering/labs--research/labs/frugal-innovation-hub/water-climate-lab/central-valley/cv-salts-program/.

Lockhart, K.M, King, A. M., & Harter, T. (2013). Identifying Sources of Groundwater Nitrate Contamination in a Large Alluvial Groundwater Basin with Highly Diversified Intensive Agricultural Production. *Journal of Contaminant Hydrology 151*, 140–154. https://doi.org/10.1016/j.jconhyd.2013.05.008

Liu, C.W., Sung, Y., Chen, B.C., & Lai, H.Y. (2014). Effects of nitrogen fertilizers on the growth and nitrate content of lettuce (Lactuca sativa L.). *International Journal of Environmental Research and Public Health, 11*(4), 4427–4440. https://doi.org/10.3390/ijerph110404427

Manassaram, D. M., Backer, L. C., & Moll, D. M. (2007). A review of nitrates in drinking water: maternal exposure and adverse reproductive and developmental outcomes. *Ciencia & saude coletiva*, *12*(1), 153–163. https://doi.org/10.1590/s1413-81232007000100018

Mathewson, P. D., Evans, S., Byrnes, T., Joos, A., & Naidenko, O. V. (2020). Health and economic impact of nitrate pollution in drinking water: a Wisconsin case study. *Environmental monitoring and assessment*, *192*(11), 724. https://doi.org/10.1007/s10661-020-08652-0.

Mission Ranches Company LLC. & Naraghi Family (2013, June 21) *Water Replacement Plan for San Lucas Community.* California State Water Resources Control Board.

MKN & Associates, Inc. (2025, February 25). *Final engineering report: San Lucas water system improvements*. California State Water Resources Control Board.

Moore, E., Matalon, E., Balazs, C., Clary, J., Firestone, L., De Anda, S., & Guzman, M. (2011). *The Human Costs of Nitrate-contaminated Drinking Water in the San Joaquin Valley*. Pacific Institute. https://pacinst.org/wp-content/uploads/2013/02/nitrate_contamination3.pdf

National Cancer Institute. (2025, April). *Cancer trends progress report: Nitrate*. National Institutes of Health, U.S. Department of Health and Human Services. https://progressreport.cancer.gov/prevention/chemical_exposures/nitrate.

Pace, C., Balazs, C., Bangia, K., Depsky, N., Renteria, A., Morello-Frosch, R., & Cushing, L. J. (2022). Inequities in Drinking Water Quality Among Domestic Well Communities and Community Water Systems, California, 2011–2019. *American journal of public health*, *112*(1), 88–97. https://doi.org/10.2105/AJPH.2021.306561

Pennino, M. J., Compton, J. E., and Leibowitz, S. G. (2017) Trends in Drinking Water Nitrate Violations Across the United States. *Environmental Science & Technology 51*(22) , 13450–13460.

Rajabi, A., Bairami, S., & Shahryari, A. (2025). Human health risk assessment of nitrate in repeatedly boiled water using Univariate regression and Monte Carlo simulation. *Scientific Reports 15*(1), 24059.

Richards, J., Chambers, T., Hales, S., Joy, M., Radu, T., Woodward, A. J., Humphrey, A., Randal, E., & Baker, M. G. (2022). Nitrate contamination in drinking water and colorectal cancer: Exposure assessment and estimated health burden in New Zealand. *Environmental Research 204,* 112322.

Fossen Johnson S. (2019). Methemoglobinemia: Infants at risk. *Current problems in pediatric and adolescent health care*, *49*(3), 57–67. https://doi.org/10.1016/j.cppeds.2019.03.002

Schullehner, J., Hansen, B., Thygesen, M., Pedersen, C. B., & Sigsgaard, T. (2018). Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study. *International journal of cancer*, *143*(1), 73–79. https://doi.org/10.1002/ijc.31306

Self, J.R., and R.M. Waskom. (2025, August) *Nitrates in Drinking Water.* Colorado State University Office of Engagement and Extension. extension.colostate.edu/resource/nitrates-in-drinking-water/.

Sum S. (2024). Impact of Droughts on Served Drinking Water Disparities in California, 2007-2020. *American Journal of Public Health, 114*(9), 935–945. https://doi.org/10.2105/AJPH.2024.307758

Tajtáková, M., Semanová, Z., Tomková, Z., Szökeová, E., Majoros, J., Rádiková, Z., Seböková, E., Klimes, I., & Langer, P. (2006). Increased thyroid volume and frequency of thyroid disorders signs in schoolchildren from nitrate polluted area. *Chemosphere*, *62*(4), 559–564. https://doi.org/10.1016/j.chemosphere.2005.06.030

Tariqi, A. Q., & Naughton, C. C. (2021). Water, health, and environmental justice in California: Geospatial analysis of nitrate contamination and thyroid cancer. *Environmental Engineering Science*, *38*(5), 377–388. https://doi.org/10.1089/ees.2020.0315

Temkin, A., Evans, S., Manidis, T., Campbell, C., & Naidenko, O. V. (2019). Exposure-based assessment and economic valuation of adverse birth outcomes and cancer risk due to nitrate in United States drinking water. *Environmental Research*, *176*, 108442. https://doi.org/10.1016/j.envres.2019.04.009

Tomich, T. P., Brodt, S. B., Dahlgren, R. A., & Scow, K. M. (Eds.) (2016). *Executive summary: The California nitrogen assessment: Challenges and solutions for people, agriculture, and the environment.* University of California, Davis, Agricultural Sustainability Institute. https://asi.ucdavis.edu/sites/g/files/dgvnsk5751/files/inline-files/Executive%20Summary%20Layout_FINAL_reduced.pdf

UC Merced, Agriculture and Natural Resources. (n.d.) *Getting Your Water Tested.* California Institute for Water Resources, UC ANR, ciwr.ucanr.edu/Tools/Drinking_Water/fs2_e/index.cfm.

Volzer, H., Blatt, A., Richerson, H., & Walling, S. (2025, September). *Nitrates on Tap: The Cost of Nitrate Contamination in Wisconsin's Drinking Water.* Alliance for the Great Lakes, Clean Wisconsin. https://www.cleanwisconsin.org/wp-content/uploads/2025/10/AGL_NitrateReport_Sept2025_Final.pdf

Walton, G. (1951). Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water. *American Journal of Public Health and the Nation's Health, 41*(8), 986–996. https://doi.org/10.2105/AJPH.41.8_Pt_1.986

Wang, Z., & Li, S. (2004). Effects of Nitrogen and Phosphorus Fertilization on Plant Growth and Nitrate Accumulation in Vegetables. *Journal of Plant Nutrition, 27*(3), 539–556. https://doi.org/10.1081/pln-120028877

Ward, M. H., Rusiecki, J. A., Lynch, C. F., & Cantor, K. P. (2007). Nitrate in public water supplies and the risk of renal cell carcinoma. *Cancer causes & control: CCC*, *18*(10), 1141–1151. https://doi.org/10.1007/s10552-007-9053-1

Ward, M. H., Jones, R. R., Brender, J. D., de Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M., & van Breda, S. G. (2018). Drinking Water Nitrate and Human Health: An

Updated Review. *International Journal of Environmental Research and Public Health*, *15*(7), 1557. https://doi.org/10.3390/ijerph15071557

World Health Organization. (2019, November 20) *Information Note Nitrosamine Impurities.* www.who.int/news/item/20-11-2019-information-note-nitrosamine-impurities.

Yates, G., Burke, M., & Feeney, M. (2011, June 6). *Nitrate Concentrations in Groundwater near San Lucas.* Monterey County Redevelopment and Housing Office.

Yousefi, H., & Karimi Douna, B. (2023). Risk of Nitrate Residues in Food Products and Drinking Water. *Asian Pacific Journal of Environment and Cancer, 6*(1), 69-79. https://doi.org/10.31557/apjec.2023.6.1.69-79

Zeegers, M. P., Selen, R. F., Kleinjans, J. C., Goldbohm, R. A., & van den Brandt, P. A. (2006). Nitrate intake does not influence bladder cancer risk: the Netherlands cohort study. *Environmental health perspectives*, *114*(10), 1527–1531. https://doi.org/10.1289/ehp.9098

Zivin, J. G., Neidell, M., and Schlenker, W. (2011) Water Quality Violations and Avoidance Behavior: Evidence from Bottled Water Consumption. *The American economic review* *101*(3), 448–453. https://doi.org/10.1257/aer.101.3.448