

Water Security and Nutrition: Current Knowledge and Research Opportunities

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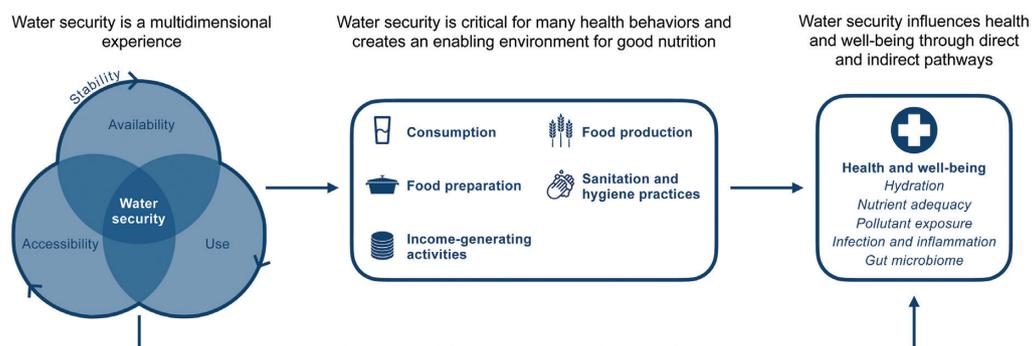
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ABSTRACT

Water is an essential nutrient that has primarily been considered in terms of its physiological necessity. But reliable access to water in sufficient quantities and quality is also critical for many nutrition-related behaviors and activities, including growing and cooking diverse foods. Given growing challenges to water availability and safety, including climate change, pollution, and infrastructure degradation, a broader conceptualization of water and its diverse uses is needed to sustainably achieve global nutrition targets. Therefore, we review empirical and qualitative evidence describing the linkages between water security (the reliable availability, accessibility, and quality of water for all household uses) and nutrition. Primary linkages include water security for drinking, food production and preparation, infant and young child feeding, and limiting exposure to pathogens and environmental toxins. We then identify knowledge gaps within each linkage and propose a research agenda for studying water security and nutrition going forward, including the concurrent quantification of both food and water availability, accessibility, use, and stability. By making explicit the connections between water security and nutritional well-being, we aim to promote greater collaboration between the nutrition and water, sanitation, and hygiene sectors. Interdisciplinary policies and programs that holistically address the water–nutrition nexus, versus those that focus on water and nutrition independently, are likely to significantly advance our ability to ensure equitable access to healthy foods and safe water for all. *Adv Nutr* 2021;12:2525–2539.

Statement of Significance: We present the most comprehensive review of the intersections between water security and nutrition to date. We also identify research opportunities that can mutually advance objectives in both sectors.

GRAPHICAL ABSTRACT



Keywords: diet, food security, hygiene, infant and young child feeding, nutrition, water security, water quality

Introduction

Water is an essential nutrient that is fundamental for maintaining homeostasis. But the value of water extends beyond its physiological necessity. Reliable access to water in sufficient quantities and quality for a healthy life, or “water security” (1), is critical for agricultural food production and preparation, personal hygiene, and psychological well-being (2, 3). In other words, water security creates an enabling environment for good nutrition. Yet, few studies to date have considered the role of water security in nutrition.

Water security is a multidimensional concept that includes water availability (whether water is in the physical environment), accessibility (whether water can be acquired through socially acceptable means), use (whether there is enough safe and acceptable water for all needs), and stability across time (Figure 1) (4). Water insecurity is a state when 1 or more of these dimensions are compromised and can manifest due to problems with water scarcity, excess (e.g., flooding), or contamination. Experiential scales at the household and individual level have gained prominence in global public health as a useful way to quantify complex lived experiences and explore how resource insecurities shape behavior and well-being. For instance, the development and broad implementation of experience-based food-insecurity scales have exposed persistent nutrition inequities that are masked by less granular data (e.g., calories per capita estimated from food balance sheets) (5). The recent development of validated metrics for comparably measuring water security across diverse contexts (6, 7) has similar potential to greatly expand our knowledge by allowing for empirical assessment of the many plausible linkages between water security, food security, diet, and health (3, 8–10).

More than 2 decades ago, experts at the World Water Congress warned that issues with water availability, namely water scarcity and flooding, would become major constraints to food production and exacerbate food insecurity (11). As predicted, global hunger is currently on the rise and is most acute in regions where historical rainfall patterns are shifting due to climate change, resource management is poor, and access to irrigation technologies is not equitable across users (12). Similarly, early application of validated experiential water-insecurity scales has demonstrated that food and water insecurity often co-occur (13, 14), and that water insecurity may precipitate future food insecurity (15). These findings suggest that greater consideration of water

insecurity is necessary for improving nutrition and health globally (8, 16).

We therefore seek to synthesize available evidence on the physiological importance of water and the myriad intersections between water security and nutrition. We first consider the role of water as a beverage and then examine its function in the food supply chain, from production to consumption. For each linkage, we present major findings to date and guide readers toward foundational reports or reviews that cover particular topics in greater depth. We primarily draw on articles published within the prior decade, but also consider older articles if the topic has been underresearched. Given that water insecurity is a global phenomenon that occurs in both high- and low-income countries (6, 17), we did not impose a geographical restriction; relevant contextual details about the study populations and local water typologies are provided to inform generalizability to other settings. We conclude by identifying policy and programmatic approaches for improving water security and nutrition synergistically.

Current Status of Knowledge

Water as an essential nutrient

As the largest constituent of the human body, water’s critical role in health and well-being cannot be overstated: without water, life cannot occur (18). It serves as a universal solvent; aids in nutrient digestion, absorption, transport, and metabolism; stores and dissipates heat for thermoregulation; maintains osmotic gradients and action potentials; and provides protection as a physical shock absorber (19). Paradoxically, our body’s most important nutrient may be the most overlooked and underresearched within the field of nutrition (20–22).

Total body water accounts for >50% of body weight but varies based on sex and body composition (e.g., adipose tissue stores less water than lean body mass) (23). Water is primarily lost through urine, respiration, sweat, and feces. Fluid balance (i.e., euhydration) is maintained by matching output with inputs, including direct fluid intake and consumption of foods that contain water (24). Numerous feedback mechanisms exist to ensure euhydration by modifying excretion (e.g., antidiuretic hormone and aldosterone increase reabsorption of water in nephrons) and regulating thirst. Net water loss results in dehydration and repeated episodes increase the risk of numerous morbidities, from urolithiasis to chronic kidney disease (24, 25).

A 1–2% loss of body water (i.e., mild dehydration) can cause fatigue and impair cognitive function (24, 26). Dehydration reduces brain volume and has inconsistently been found to be associated with worse mood and cognition, although normal attention, memory, and other executive functions can be restored following fluid restoration (27, 28). Elderly individuals have a blunted thirst signal and are thus at higher risk of dehydration (29). Young children and elderly adults may also be more severely impacted by the effects of dehydration on cognition than other age groups (27).

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Abbreviations used: EED, environmental enteric dysfunction; SSB, sugar-sweetened beverage; WaSH, water, sanitation, and hygiene.

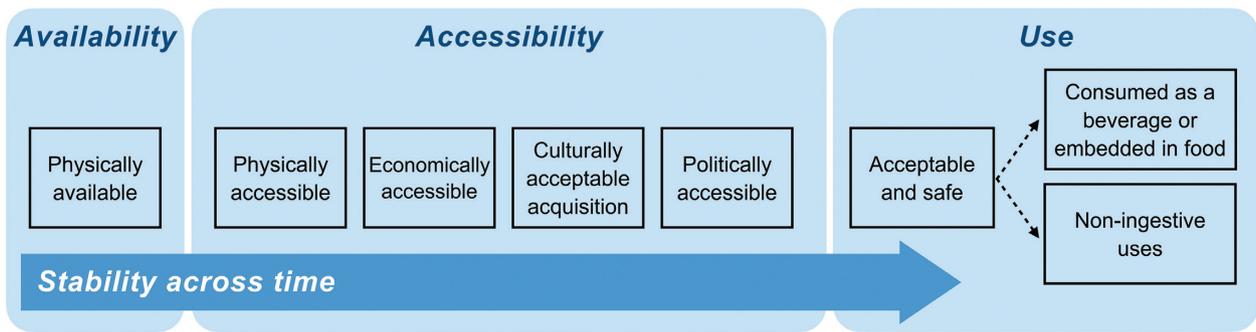


FIGURE 1 Primary domains of water security include availability (whether water is available in the environment), accessibility (whether water is affordable and able to be procured in a socially acceptable manner), use (whether there is enough water of sufficient quality for all household needs), and stability across time; water quality is inherent in each domain. Adapted from references 9 and 30.

Water for drinking

Plain drinking water and other beverages.

Water is the optimal beverage for maintaining euhydration (31). Yet, few studies or national reporting agencies systematically measure hydration status or collect drinking water intake data (32); fewer still consider the ways by which water embedded in foods and other beverages (i.e., “virtual water”) contribute to hydration status (26). Limitations with current methodologies for assessing water intake and hydration status (e.g., recall bias, nonspecific biomarkers) have made it difficult to establish adequate intake values (33–36). These knowledge gaps are well articulated in the 2020 Dietary Guidelines Advisory Committee Scientific Report, which notes that “the degree to which hydration is a problem in segments of the population is an open question” and “better information about water intake is needed” (32). More research is required to understand how water requirements vary by climate, body composition, life stage, disease state, and diets. Such information can then be used to track the prevalence of suboptimal hydration across time and populations (32).

Non-water beverages have varied impacts on hydration status. Alcoholic and caffeinated drinks induce diuresis, although caffeine intake rarely meaningfully impacts overall water balance (37, 38). In contrast, juices and some sugar-sweetened beverages (SSBs) can help to restore total body water (39). But caloric beverages also contribute to excess calorie intake and thereby increase the risk of overweight and obesity, as well as their associated sequelae (39). Replacing caloric beverages with plain water reduces energy intake, increases fat oxidation, and can be a useful strategy for weight maintenance (31).

Individuals may preferentially consume non-water beverages for their taste, cost, convenience, perceived nutritional value, or sociocultural importance, but also because of distrust about the provenance and quality of their drinking water (40) or problems related to water access (41). This is significant given that water mistrust is common globally and occurs even in settings with piped water systems (42). For instance, qualitative research in rural New Mexico found that

students avoided drinking tap water at school because it was perceived to be of poor quality and instead opted for more readily accessible SSBs (43). Such barriers to reliably accessing clean drinking water, including infrastructural disparities and environmental racism (17), may partly explain varying trends in SSB and plain water intake between racial groups and socioeconomic strata (44–46). Given the increase in noncommunicable disease prevalence, nutrition experts have identified the need to understand how experiential water insecurity influences beverage intake as a priority research area, noting that water-insecurity screening questionnaires could be used by health professionals to develop more tailored interventions (47).

Nutrients dissolved in drinking water.

The concentrations of essential minerals in most drinking water sources are typically too low to meaningfully contribute to overall intake, but there are exceptions (48). Millions of individuals live in watersheds that have “hard” groundwater, meaning that the water has high concentrations of dissolved minerals like calcium and magnesium. These metal cations are largely removed through industrial water treatment and purification processes or by at-home water-softening systems. As a result, the contribution of drinking water to recommended daily intakes of magnesium and calcium varies considerably (49, 50), but, on average, supplies 5–20% of daily intake globally (51). Epidemiologic evidence suggests that higher levels of magnesium in drinking water are associated with lower risk of ischemic heart disease and stroke mortality (52–54), and that higher calcium concentrations are associated with both greater bone mineral density and lower risk of hip fracture (54, 55).

Sodium is another essential nutrient that is typically found in low concentrations in drinking water, although this may change given greater saltwater intrusion in many settings from increasing groundwater withdrawal and sea-level rise (56). Drinking water high in salt content may contribute to excess sodium intake and concomitant hypertension (57–60), particularly among individuals with a salt-sensitive phenotype (61); these risks may be attenuated if levels of

calcium and magnesium in the water are also high (62). Notably, most studies examining the relation between water salinity and health have been conducted among coastal communities in Bangladesh, even though drinking water salinity is increasing elsewhere, such as northern Kenya (63).

Fluoride is naturally present in some water sources and added artificially in a small subset of communities globally to strengthen enamel, protect against dental caries, and improve bone health (64). Excess fluoride intake can, however, cause fluorosis and is endemic in many regions with high geologic sources of fluoride (65). There is ongoing scientific and political debate as to whether water fluoridation is the safest and most cost-efficient method for increasing exposure to fluoride in beneficial quantities (66).

Medication and micronutrient supplementation adherence.

Fluids are necessary for taking some medications and micronutrient supplements. Only a small amount of water is needed to swallow pills (67), but some medicines require up to an additional 2 L of water to metabolize (68). Moreover, water is often needed to prepare the foods to which point-of-use micronutrient powders are applied (69).

Few studies have examined water insecurity in relation to medication and micronutrient supplement adherence. A study among postpartum women in western Kenya found that 26.6% of participants or members of their households had been unable to take medicines due to problems with water, although the types of problems and medicines were not specified (70). Future studies should investigate if water insecurity is a barrier to medication adherence in other settings and identify the contextual factors that contribute to this relation.

Disordered eating.

Eating disorders such as anorexia and bulimia nervosa have the highest death rates of any psychiatric disorder (71). They are most commonly documented in high-income countries, but the prevalence of eating disorders is increasing in low- and middle-income countries (72). Eating disorders are primarily defined by dramatic changes in food intake or eating patterns, but disordered fluid intake, including water restriction and excess water intake, is also a common sign (73). Some individuals water load—potentially to the point of water intoxication (74, 75)—to blunt hunger or aid in purging behavior (73, 76), while others misuse diuretics to reduce weight (77). Both behaviors, as well as excessive exercise and purging through self-induced vomiting, can cause severe shifts in fluid volume and increase the risk of impaired osmoregulation, hypotension, cardiac arrhythmia, and death (77, 78). Increasing research on and awareness about the symptoms and characteristic behaviors associated with eating disorders, including altered fluid intake, may lead to earlier diagnosis and treatment.

Exercise and physical activity.

Traveling to and fetching water from off-premises water sources necessitates considerable energy expenditure that may increase an individual's risk of undernutrition (79). Fetching water may also indirectly impact nutrition by taking away time from income-generating activities (80, 81) or leading to injuries that prevent food purchase, production, or preparation (82). One study among individuals living in a rural village in Laos estimated that, on average, 12.8% of daily calories consumed were spent on water fetching during the dry season (83). This is substantial given that millions of households globally rely on water sources that require >30 min for roundtrip collection (80).

To estimate the degree to which water fetching contributes to energy imbalance, frequency and duration of water collection could be included in physical activity or time-use questionnaires. Geospatial technologies and accelerometers could also be used to better understand the relation between water access, collection, and energy expenditure (84, 85). Expenditure estimates should be sex and age disaggregated, given that the physical (as well as mental and social) toll of water collection is disproportionately borne by women and girls (80, 86).

Water needs for athletes vary depending on the type and duration of the activity, environmental factors, and individual characteristics. An emergent subfield within sports nutrition is examining when fluids should be consumed to maximize performance (87) and the importance of virtual water for athlete hydration (88). In some settings, water insecurity may be a barrier to exercise. For instance, individuals living in the United Kingdom reported that they altered their fitness routines following an unexpected water supply loss because they were too stressed about finding water for other uses or feared they would not be able to maintain hygiene norms (89). More research is needed to determine whether this is a localized phenomenon or common across populations.

Water for food production

Agricultural productivity.

Water is fundamental for food production and the success of crops, livestock, and aquaculture. In fact, at least 70% of freshwater withdrawals worldwide are for agriculture (90, 91). But intensifying water scarcity and extreme weather events due to climate change, as well as increasing water demands from other sectors, present substantial barriers to achieving global food security (90, 91). Understanding the bidirectional links between water security and agricultural productivity is thus critical for sustainably increasing food production to support growing populations and changing dietary patterns (8, 92).

Broadly, there are 2 distinct water typologies relevant for food production: “green water,” which refers to moisture from rainwater, and “blue water,” which is water from surface or groundwater sources (93). Rainfed agriculture (which relies exclusively on green water) is typically less productive than irrigated operations because it is more susceptible to

climatic shocks and the vagaries of local weather conditions. This is evidenced by the widening yield gap (a metric that compares the actual yield of a particular cultivar compared with its potential yield under optimal conditions) between many rainfed and irrigated crops (94). Yet, most farmers worldwide do not have access to the necessary financial or infrastructural resources to benefit from irrigation (95). Current strategies to increase agricultural yields, and ultimately reduce rates of undernutrition, involve expansion of irrigation (96) and modifying crops to be more drought resistant and water efficient (“more crops per drop”) (97).

Dietary patterns also influence food production in ways that impact global water security. A systematic review estimated that shifting from a typical “Western” diet to less resource-intensive dietary patterns—namely, replacing animal-based with low-impact, plant-based foods—could reduce overall water use by 50% (98). Reducing food spoilage and loss is also an important strategy for reconciling increasing food and water demands as nearly one-fifth of the water used for agriculture is embedded within food that is wasted throughout the supply chain (99).

Irrigation technologies.

Desalination and wastewater recycling are 2 technological solutions with potential for improving agricultural water security (100–102). Desalination is a process by which minerals dissolved in water are removed to make otherwise phytotoxic waters (i.e., water with mineral concentrations that are harmful to plants) safe for agricultural use and human consumption (102–104). Nutrients necessary for plant survival must then be added to the desalinated water, making the entire process expensive in terms of economic and environmental costs (105).

Wastewater reclamation is a process by which sewage is recycled for productive uses. Treated wastewater is often higher in many nutrients necessary for plant growth (e.g., nitrogen, phosphorus, and magnesium) than groundwater sources, thereby reducing fertilization costs (106–108). But wastewater can also have high salinity, which can negatively impact soil structure and crop productivity (104, 108). Untreated or partially treated wastewater applied to crops can also be a vector for water- and foodborne pathogens (109, 110). Combining treated wastewater and desalinated water is an emerging method that mitigates many costs of both technologies while preserving their benefits (101, 102).

Access to irrigation technologies can both directly and indirectly improve nutritional well-being (111). Greater agricultural yields can increase a household’s income, allowing individuals to purchase more (diverse) food (112). Further, irrigation technologies that produce clean water (e.g., desalination) can function as multiple-use water systems, meaning individuals can use the expanded water supply for other household needs, like water, sanitation, and hygiene (WaSH) activities that ensure the safe handling and preparation of foods (2). Another potential mechanism of action is through expanded women’s empowerment.

Small-scale irrigation can be a catalyst for women’s empowerment by increasing asset ownership and income, as well as decreasing the time burdens associated with water fetching (8). Given that women in many settings are primarily responsible for food preparation and caregiving, it is hypothesized that women with greater autonomy and decision-making capabilities will dedicate more resources to improving nutritional adequacy, particularly among children (113, 114). The relation between women’s empowerment and child nutrition remains unclear, however, due to the diversity of methods used to measure women’s empowerment (115). Future nutrition-sensitive agriculture interventions could help fill this knowledge gap by measuring water insecurity, nutrition outcomes, and women’s empowerment using validated instruments at multiple stages of project implementation (8, 111, 116, 117).

Water for food preparation and infant and young child feeding

Food preparation.

Water is needed for food hygiene, particularly cleaning fruits and vegetables. Washing foods with clean water can remove harmful pesticides or residual soil matter that may contain parasitic helminths that cause intestinal bleeding and reduce the host’s ability to absorb nutrients (118). Water is also needed to clean utensils for serving and consuming foods (119). Use of pathogen-contaminated water for any of these activities can increase the risk of diarrhea (120, 121). Future research should consider the ways by which water insecurity may impact food handling safety, meal preparation, and feeding (122–124).

Starchy staples often require water to improve palatability and digestibility as well as to remove toxins. For instance, cassava is a drought-resistant, carbohydrate-rich crop that is common in many diets throughout sub-Saharan Africa and must be soaked or boiled in water to remove neurotoxic cyanogenic glucosides (125). During periods of water scarcity, many food-insecure households consume underprocessed cassava, as evidenced by variations in the prevalence of konzo (a neurologic disorder resulting from cyanide exposure) that track seasonal fluctuations in rainfall and water availability (126).

Households may cope with water scarcity and contamination by consuming less food or changing diets, sometimes replacing preferred foods with less nutrient-dense or more highly processed substitutes that require little or no water to prepare (127). In Kenya, 2 studies found that households had sufficient food but were unable to use it because they lacked water (e.g., for preparing porridge) (81, 128). Similarly, women in South Africa reported that unexpected water supply interruptions limited their ability to cook and prepare meals (129). In other settings, individuals may cope with poor water quality by limiting fluid intake and increasing consumption of water-rich foods to maintain euhydration (130).

Like many food-insecure households, households experiencing water issues may consume more meals outside the

home (131). Such foods tend to be more calorie dense and higher in saturated fats than those prepared at home (132). One study in the Galápagos found that concurrent exposure to poor water access and food insecurity was associated with greater odds of the dual burden of malnutrition in households (133), suggesting that problems with water may be a risk factor for overweight and noncommunicable disease. More systematic investigation is required to understand how other components of water insecurity influence a household's ability to prepare foods and how this, in turn, affects meal frequency, size, and composition.

Human-milk quality and quantity.

Water is the primary component of human milk (134), such that lactating individuals require greater water to compensate for fluid loss through milk synthesis (135) and are at higher risk of dehydration, particularly in hot-humid climates (136). Previous studies have found no association between fluid restriction and human-milk supply, although the majority were conducted among small study samples and measured milk production indirectly (e.g., weighing infants pre- and postfeeding) (137). The paucity of data is evidenced by a Cochrane review that deemed the only modern trial examining fluid intake and human-milk production to be of low quality and at high risk of bias (138). It is possible that mammals have evolved to prioritize milk production during times of water scarcity to ensure offspring survival (137)—similar to how maternal macronutrients are preferentially shunted to the developing fetus during pregnancy (139)—although more research is needed to understand the mechanisms that control milk synthesis during water restriction.

Water insecurity may also limit human-milk production through psychosocial mechanisms. Greater household water insecurity has been found to be associated with greater perceived stress (6); increased sympathetic nervous system activity can, in turn, impair lactogenesis and lead to decreased milk output (140). Perceived milk insufficiency or inadequacy may also lead caregivers to introduce non-human-milk foods too early (141). More robust research is needed to understand how dehydration, and water insecurity more broadly, impacts milk production, especially given that many lactating individuals do not meet adequate fluid intake levels (142). Deuterium oxide (i.e., doubly labeled water) dose-to-the-caregiver techniques have provided novel insights into how food insecurity impacts breastfeeding (143) and could be similarly informative for understanding how water insecurity shapes human-milk production and feeding.

Environmental exposures, including polluted water, can adversely affect human-milk quality. Lactating caregivers exposed to heavy metals through drinking water have higher circulating blood concentrations of these toxic compounds, which can be incorporated into human milk and consumed by infants (144, 145). This is significant because rapid brain development and myelination occur during infancy, meaning that repeated heavy metal exposure during this sensitive period, even at low levels, can result in lifelong neurocognitive deficits (146, 147). Importantly, exclusive

human-milk feeding remains the preferred feeding method, even in settings with high environmental burdens. Infant formula and other foods prepared with contaminated water can expose infants to waterborne pathogens or harmful chemicals (148–150) that cannot pass from caregiver to infant via human milk. Indeed, the inappropriate marketing of infant formula to caregivers without access to clean water in low- and middle-income countries during the late 20th century caused tens of thousands excess infant deaths (151). Initiatives to promote human-milk feeding should therefore include strategies to address persistent caregiver misconceptions that water supplementation during the first 6 mo of life is needed to prevent infant dehydration (152–154).

The physical burdens and opportunity costs associated with water insecurity present additional barriers to exclusive human-milk feeding. A prior cross-cultural study spanning 16 low- and middle-income countries found that greater time spent fetching water was perceived to limit caretakers' abilities to exclusively offer human milk or feed at the breast (155). In a separate study, Ghanaian mothers also reported that the time and physical burdens associated with hauling water limited their ability to breastfeed (156). Future studies can build on these qualitative findings by empirically assessing the relation between household water insecurity and human-milk feeding initiation, duration, and exclusivity.

Complementary feeding.

To date, most studies during the complementary feeding period have only considered water as a potential vector for pathogenic organisms (157, 158). But, as described above, problems with water can also limit the diversity and quantities of foods a household is able to purchase, produce, or prepare (e.g., insufficient water to make foods soft enough for young infants to swallow). One study drawing on nationally representative Demographic and Health Survey data from India found that optimal household water access was associated with a higher odds of an infant meeting minimum dietary diversity, compared with intermediate or basic access (159). Seasonal variations in rainfall and associated impacts on food availability have also been described as influencing the age at which complementary foods are introduced (155, 160). Beyond water quality and availability, qualitative evidence suggests that problems with water access and use can lead caregivers to substitute preferred dishes with less nutrient-dense foods (155). The time and opportunity costs associated with water insecurity may also limit the ability of caregivers to notice feeding cues or apply optimal responsive-feeding practices (161). Ultimately, more systematic investigation is needed to understand how common these experiences are and assess their magnitudes of effect.

Water as an environmental exposure

Pathogens, heavy metals, and emerging water pollutants.

There has been substantial progress in expanding access to safely managed drinking water sources in the prior 3 decades, but unsafe water still significantly contributes to the global burden of disease, even in high-income countries (162). For

instance, it is estimated that 12–19 million cases of gastrointestinal illness in the United States are attributable to contaminated drinking water each year (163). The relative health risks of each water contaminant are based on their mechanism of action, concentration, and duration of exposure. Whereas waterborne pathogens can cause illness after brief exposures, chemical contaminants are typically most harmful when consumed for prolonged periods of time (164).

There are hundreds of known waterborne pathogens, which include viruses, bacteria, parasitic protozoa and helminths, and fungi. Regulatory agencies have the capacity to systematically monitor only a small subset (164, 165), such that the true burden of waterborne diseases is likely underestimated due to infrequent or nonspecific testing and an inability to determine etiology in many cases of illness (166). Available data, however, suggest that viruses are the most common cause of gastrointestinal distress globally (167). Bacterial pathogens such as *Vibrio cholerae* and *Salmonella enterica* are also responsible for numerous outbreaks of enteric illness, particularly in settings with limited access to improved water sources (165). Inhalation of mist containing bacteria can also cause respiratory disease. Outbreaks of Legionnaires' disease, for instance, are most often attributed to poor water treatment and infrastructure maintenance (e.g., infrequent cleaning of heating, ventilation, and air conditioning systems) in communities with centralized piped water networks (168, 169). Finally, antibiotic-resistant bacteria in drinking water are also becoming increasingly common and pose significant health risks when resistance is transferred to human pathogens (170).

Water can also be problematic due to heavy metal or chemical contamination. Heavy metals that pose the greatest threats to human health include cadmium, lead, mercury, and arsenic; their impacts on nutrient metabolism have been thoroughly described elsewhere (171). Briefly, heavy metals can be detrimental by acting as competitive inhibitors and interfere with, for example, iron metabolism, erythropoiesis, and bone formation (172). Heavy metals can also alter the composition of the gut microbiota and induce dysbiosis (173). Interestingly, an individual's nutritional intake can moderate the impacts of heavy metal exposure. For instance, a double-blind trial among individuals living in an area with naturally occurring arsenic in the groundwater found that folic acid supplementation increased arsenic methylation and reduced its harmful sequelae (174).

Pollutants of emerging concern are those that are not commonly monitored or regulated but have known or suspected human health risks (175). Hundreds of these emerging pollutants have been identified and include pharmaceuticals, personal care products, industrial and household byproducts, metals, microplastics, industrial additives and solvents, and artificial sweeteners (175, 176). The types, prevalence, and concentrations of emerging pollutants vary substantially across regions, water sources, and season (177, 178). Our understanding about their nutritional impacts is in its infancy, but the relation is likely bidirectional: some emerging contaminants may affect nutrient absorption and

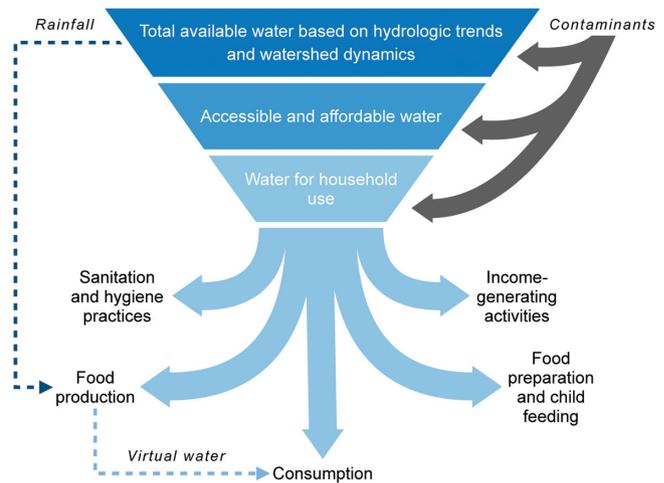


FIGURE 2 Water security is shaped by factors at multiple socio-ecological levels, from environmental conditions (dark blue) to inhousehold dynamics (light blue). Problems at any level can have negative impacts on downstream water uses and thereby influence nutrition, health, and well-being.

nutrition may modulate the toxicity of these pollutants (179). The development of low-cost, easy-to-use, field-deployable water diagnostics is needed to advance our ability to detect, research, and develop solutions for water contamination (164, 180).

Strategies to improve water quality should account for the multiple routes and types of exposure, from the watershed (e.g., agricultural runoff) to household level. Increasing access to piped water sources can improve household water security, but potable water collected from an improved water source can be rendered unsafe if gathered with or stored in a contaminated container (181, 182). For this reason, interventions are often most effective at reducing diarrhea risk if they improve source quality and provide a safe water storage container (183). Household coping strategies may also modify risk from contaminated water and should be considered when designing interventions. For instance, interhousehold water sharing is a common practice among water-insecure families and could expose individuals to greater disease risk if the borrowed water is contaminated (184, 185).

Diarrhea and environmental enteropathy.

The role of water in child growth and mortality has most frequently been considered in terms of its impact on diarrhea, which is typically caused by 1 or more of the waterborne pathogens described above. It is estimated that nearly three-quarters of the almost 450,000 diarrhea deaths among children under 5 in 2016 can be attributed to unsafe water and sanitation (186), as well as 16% of stunting among children under 5 in low- and middle-income countries (187).

Environmental enteric dysfunction (EED), a complex condition characterized by chronic intestinal inflammation, flattened villi, and greater gut permeability, may be an important mediator between water and child development (188). Currently, few noninvasive tests are available to

diagnose EED and none are sufficiently specific to distinguish EED from other intestinal infections, such that the pathogenesis of EED and its mechanisms of action have yet to be thoroughly described (189, 190). Most likely, EED is the result of repeated exposure to 1 or more pathogens that ultimately alter the structure and function of the gut (190). Numerous observational studies have found that indicators of EED are associated with suboptimal nutrient absorption, stunted linear growth, restricted early childhood development, and lower oral vaccine effectiveness (188, 191–194). Based on these findings, 3 large-scale randomized trials aimed to reduce the incidence of childhood diarrhea and stunting by limiting environmental exposure to pathogens through improvements in both sanitation and hygiene practices and drinking water quality (195–197). These interventions had mixed impacts on diarrhea and no effect on child linear growth (198). A subset of participants in the Zimbabwe trial were enrolled into a substudy to assess impacts on EED; the WaSH intervention did not have a major impact on any of the EED biomarkers (199). Taken together, these studies suggest that more expansive strategies that address additional routes of exposure and other dimensions of water insecurity beyond quality (i.e., “transformative WaSH”) may be needed to meaningfully reduce the risk of EED (198). Advancements in the methods used to identify EED are also needed for more accurate diagnosis and earlier treatment (190).

Microbiome and inflammation.

The diversity and stability of the gut microbiome is responsive to a wide range of dietary and environmental factors (200, 201) and may therefore be directly influenced by the quality and quantity of available drinking water, with direct consequences for metabolism, immune function, and resistance to infectious pathogens (202–204). Each drinking water source has a unique, dynamic microbiome that can alter the composition of an individual’s gut microbiota directly or by changing the gut ecology (205, 206). For example, Himalayans who drank river water had higher abundances of *Treponema* and lower levels of *Fusobacterium* compared with those who drank underground water, suggesting that each water source contained different microbes (207). Likewise, the gut microbiota of the Hadza, a forager group in East Africa, differed by the primary water source individuals used (207).

Along with its microbial content, the chemical properties of drinking water may also influence the gut microbiota, even in piped water sources. For instance, work in the United Kingdom has found that α -diversity (i.e., number and richness of species within a sample) was associated with the sodium, sulfate, and chloride content of tap water (208), suggesting that these minerals can differentially support bacterial communities in the gut.

Poor water quality, particularly water contaminated by enteric pathogens, may be an important factor shaping the colonization of the gut in early development. A study in Nicaragua found that infants and young children living in households with higher concentrations of total coliforms in

their drinking water had lower α -diversity and a greater relative abundance of potentially predatory or pathogenic bacteria in fecal samples relative to those using low-coliform water sources (209). This suggests that exposure to poor-quality water may render the gut more susceptible to harmful bacteria (210). Similarly, research across diverse settings has found that repeated episodes of diarrhea, caused by contaminated water or other environmental sources, are associated with lower microbiota diversity, gut dysbiosis, and chronic inflammation (211, 212).

Importantly, the psychological distress that accompanies water insecurity (213) may also influence the gut microbiota. Chronic stress has been shown to affect the development of the intestinal barrier (214), increase gut permeability (215), and contribute to gut dysbiosis (216). These, in turn, increase the risk of infection, malnutrition, overweight, and cardiometabolic disease by stimulating inflammation, insulin dysregulation, and weight gain (204, 217). Despite the known importance of environmental exposures on the gut microbiota and its associated health outcomes, relatively little work has focused on water insecurity as a multidimensional experience shaping gut colonization or diversity.

Conclusions

It is evident that water security is essential, but not sufficient, for good nutrition. As demonstrated, nutritional well-being is contingent upon the presence of both water and food security. At the food production level, improved nutrition through more efficient agricultural practices is dependent on water quality and quantity, but also crop quality, safety, diversity, and yield. At the household level, secure access to nutritious and safe foods is necessary for ensuring good health, as well as access to sufficient and safe water to prepare available foods and reduce the risk of foodborne pathogens. Within individuals, drinking water is needed for fluid balance and may enhance nutritional status by providing essential micronutrients, but the benefits are moderated by water quality, coexisting infections, nutritional status, and microbiome characteristics. Additionally, nutritional needs shift across the life course (e.g., with age, pregnancy status), including the risks for and consequences of food and water insecurity. Yet, despite their many linkages, food and water insecurity have traditionally been treated as independent challenges to health.

Current global public health efforts could be more effective by addressing water and food insecurity jointly. For instance, there are Sustainable Development Goals for food and water, but none consider their many linkages; underappreciation of the interconnections between these 2 essential resources is significant given that improvements in one can be to the detriment of the other (2). Such delineations have contributed to disciplinary siloing, although coordination between the WaSH and nutrition sectors is needed to advance the goals of each (8).

Strategies to improve nutrition must consider the diverse ways by which water availability, accessibility, quality,

stability, and use can be compromised (Figure 2). Policies that intervene upon only 1 determinant of water security may not be sufficient for improving downstream health and nutrition outcomes. As noted by implementers of 3 large-scale WaSH trials that found no effect of household-level drinking water quality improvements on child linear growth, holistic solutions that consider water security at multiple scales are needed to address seemingly intractable health issues (198). Technocratic strategies (e.g., installation of water pipes) are likely to be most effective when implemented at the utility level (218) and paired with water governance and infrastructural maintenance initiatives that ensure that water technologies are sustainably managed, adaptable to shocks, and accessible to all (i.e., do not exacerbate entrenched water inequities) (219, 220). This will require considerable financial investment, but the returns are likely to be substantial, including reductions in health care costs, expanded human capital, and greater national security (221, 222). Sustained financial and institutional support for interdisciplinary research that addresses the knowledge gaps outlined above is also necessary to inform the development of effective policies and programs (Text Box 1).

Text Box 1
Selection of policy-relevant research opportunities for better understanding how experiential water insecurity both directly and indirectly impacts nutritional well-being

- Explore how water requirements vary by body composition, life stage, disease state, and local climate to inform recommendations about water consumption and improve monitoring of dehydration across time and populations
- Assess the role of water insecurity in noncommunicable disease risk and progression through its potential impacts on:
 - Food insecurity and dietary patterns, including sugar-sweetened beverage intake and meals prepared away from home
 - Physical activity and exercise
 - Gut microbiota composition and abundance
 - Medication and supplement adherence
- Understand how water insecurity influences infant and young child feeding, particularly:
 - Perceived and actual human-milk quantity and quality
 - Human-milk feeding initiation, duration, and exclusivity
 - Timing and choice of complementary foods
 - Responsive-feeding practices
- Quantify the burden of poor water quality (including emerging pollutants) and its potential impact on disease risk and dietary decision making

Systematic collection of high-resolution data will advance our understanding of the global water crisis and identify where resources should be targeted. We encourage researchers and agencies to add validated metrics of water quality (164, 180), water-insecurity experiences (6), and markers of hydration (223) alongside traditional nutrition indicators. Data generated from these tools can be compared across settings and time to understand the dynamics of water insecurity and determine which aspects of water insecurity are key constraints to health and well-being. Further, data should be disaggregated by salient sociodemographic characteristics, such as age, gender, and income status, to determine whether progress towards water security is equitable (224). In prior decades, data generated from the implementation of experiential food-insecurity scales have been used to inform policy and bring awareness to disparities in food availability, access, and use (225); application of experiential water insecurity scales are likely to be similarly transformative (4). Ultimately, a policy and research agenda that addresses the multiple water–nutrition linkages herein will advance our ability to ensure equitable access to healthy foods and safe water for all.

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