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Title: On-plot drinking water supplies and health: a systematic review

Authors
Alycia Overbo[a]*, Ashley R. Williams[a], Barbara Evans[b], Paul R. Hunter[c], & Jamie Bartram[a]

[a]The Water Institute, University of North Carolina at Chapel Hill
[b]Institute of Public Health and Environmental Engineering, University of Leeds
[c]Norwich Medical School, University of East Anglia

*Corresponding author
135 Dauer Drive, CB#7431, Chapel Hill, NC 27599, United States
Overbo@live.unc.edu

Abstract

Many studies have found that household access to water supplies near or within the household plot can reduce the probability of diarrhea, trachoma, and other water-related diseases, and it is generally accepted that on-plot water supplies produce health benefits for households. However, the body of research literature has not been analyzed to weigh the evidence supporting this. A systematic review was conducted to investigate the impacts of on-plot water supplies on diarrhea, trachoma, child growth, and water-related diseases, to further examine the relationship between household health and distance to water source and to assess whether on-plot water supplies generate health gains for households. Studies provide evidence that households with on-plot water supplies experience fewer diarrheal and helminth infections and greater child height. Findings suggest that water-washed (hygiene associated) diseases are more strongly impacted by on-plot water access than waterborne diseases. Few studies analyzed the effects of on-plot water access on quantity of domestic water used, hygiene behavior, and use of multiple water sources, and the lack of evidence for these relationships reveals an important gap in current literature. The review findings indicate that on-plot water access is a useful health indicator and benchmark for the progressive realization of the Sustainable Development Goal target of universal safe water access as well as the human right to safe water.

Keywords: water supply; diarrheal disease; child nutritional status; geohelminth; Sustainable Development Goals

Introduction

Water access mediates the transmission and prevention of many infectious diseases. The Bradley Classification groups water-related infections in four categories: waterborne; water-washed; water-based; and water-related insect vectors (Table 1) (White et al., 1972). The categories are non-exclusive; several waterborne infectious diseases can also be water-washed (Bartram and Hunter, 2015).

[Table 1]

Access to on-plot water sources may reduce exposure to waterborne pathogens through reduced risk of contamination at the source, during collection, or during household storage (Wright et al., 2004; Bain et al., 2014b; Shields et al., 2015). Regardless of source water quality, contamination of stored water can occur when left uncovered (Hoque et al., 2006) or when hands or utensils are dipped into the container (Heitzinger et al., 2015).

Water-washed diseases may also be mitigated through proximity to water sources. Households in close proximity to their primary water sources experience less diarrhea (Gorter et al., 1991; Wang and Hunter, 2010) and trachoma (Marx, 1989; Golovaty et al., 2009). They also have been shown to spend less time collecting water (Aiga and Umenai, 2002), use greater quantities of water (Bailey et al., 1991; Polack et al., 2006), and practice improved hygiene behavior (Cairncross and Cliff, 1987; Curtis et al., 1995). Health benefits of hygiene reflect the Mills Reincke phenomenon (Sedgwick and MacNutt, 1908) of multiple health gains; for example, hygiene has been shown to reduce risk and prevalence of respiratory infections (Ryan et al., 2001; Rabie and Curtis, 2006), trachoma (Taylor et al., 1989; West et al., 1995), and diarrhea (Aung Myo and Thein, 1989; Cairncross et al., 2010). Repeated episodes of diarrhea have adverse effects on nutrition and growth in children (Black et al., 1984; Checkley et al., 2003), and the use of improved water sources, defined as water sources protected from outside contamination (WHO/UNICEF, 2012), has been associated with improved child height and weight outcomes (Tomkins et al., 1978; Esrey et al., 1988).

Individuals with on-plot access to water may enjoy health benefits through greater water availability, greater quantity of water available for hygiene, and decreased contamination risks (Figure 1). However, service reliability can affect potential health gains from on-plot water access. Households with more reliable water service have been shown to experience less diarrhea (Majuru et al., 2011) and bloody diarrhea (Ercumen et al., 2015) than households with intermittent service.

[Figure 1]

The importance of access to a water supply at home has been recognized by the international community; the percentage of the population using a safely-managed water service at home is a proposed indicator for the Sustainable Development Goal of universal access to safe drinking water by 2030 (WHO/UNICEF, 2014). Despite the evidence for health gains from improved water access, the published literature provides little insight into the scope and magnitude of health impacts achieved through having an on-plot water supply for drinking water and domestic activities compared to using a water supply off premises. Additionally, the relative impact of on-plot water access on waterborne and water-washed diseases and observed mechanisms behind health effects are unclear. To fill this gap we conducted a systematic review of peer-reviewed literature on the health impacts of on-plot water sources on a selection of water-related diseases and child growth.

Methods

The literature search was conducted in July 2013 in three databases of peer-reviewed articles, Embase, Global Health, and PubMed, and updated in January 2016. The search strategy was in English and included terms describing water sources within the household dwelling or plot, water-related pathogens, and health outcomes (Table 2), which were entered and searched concurrently. No search limits on publication date, language, or study location were used. Search results were downloaded into RefWorks (ProQuest LLC, 2016) for the removal of duplicate results and screening. The bibliographies of accepted studies were reviewed for relevant studies.

[Table 2]

Two reviewers (AO and ARW) independently screened all retrieved titles and identified potentially relevant studies for abstract review. Studies investigating water-related health outcomes, hygiene, household water access, and water supply interventions were included. The review aimed to evaluate health effects of having water supplies on premises in non-emergency settings and characterize the effects of increased water availability, therefore studies examining health outcomes in the following conditions were excluded in title screening: disease outbreaks; suspected water contamination events; natural disasters; conflicts; and refugee camps.

In abstract review, studies analyzing household water access or household environmental conditions as risk factors for water-related health outcomes were identified for full-text review. Secondary research, qualitative studies, and water quality studies lacking health outcome data were excluded.

Studies excluded in the full-text review had one or more of the following characteristics: health outcomes not included in the search strategy (Table 2); unclear definitions, diagnoses, or rationales for health outcomes; recall periods exceeding two weeks for self-reported diarrhea; and lack of statistical analysis of on-plot water supplies and health outcomes. Studies included in full-text review had all of the following characteristics: collected primary data; were conducted in non-emergency settings; conducted quantitative, statistical analysis on included health outcomes; and analyzed health effects of on-plot water access compared to off-plot water access.

On-plot water sources were defined as household piped connections (irrespective of source), yard taps, roof storage tanks, and protected and unprotected wells, provided that these were located on the premises. Some studies distinguished between ‘improved’ water sources, such as piped connections, protected springs, protected wells and rainwater harvesting, and ‘unimproved’ water sources, such as unprotected wells, tanker-trucks, bottled water, and surface water (WHO/UNICEF, 2012). When water source location or type was unclear, authors were contacted for clarification.

Full texts published in languages other than English were translated using Google

Translate. Studies published in multiple papers were included once in the review unless papers reported on different health outcomes. A single reviewer (AO) performed data extraction for accepted papers. The following study data was extracted from each paper: author; year; health outcomes analyzed; design; location and setting; dates and duration; participant selection methods; data collection methods; age and number of participants; collection of socioeconomic data; water source types; outcome definition; statistical tests; statistical findings; and statement on funding or conflict of interest. Reported findings on potential mediators of on-plot access were also extracted, including: use of multiple sources; intermittent service; water quantity and quality; and distance to water source.

Studies accepted in the full-text screening were assessed for rigor in study design and reporting. Rigor criteria relevant to all study designs and health outcomes were developed based on the STROBE reporting guidelines for observational studies (von Elm et al., 2007). Criteria were developed to address potential sources of error or bias in participant selection, measurement, setting exposures, and reporting. Rigor was assessed based on the following: description of study setting; description of study time frame; randomized or systematic participant selection; description of data collection methods; use of regression or adjusted analysis; and statement of funding or conflict of interest. Regression or adjusted analysis was weighted to account for confounder adjustment as well as individual-level analysis (Blum and Feachem, 1983). Binary classifications were used to evaluate each criterion, and the score for each study was calculated as the number of total points (scale 0–7). Studies scoring >5 were considered rigorous in study design and reporting; studies scoring ≤5 were considered less rigorous.

Meta-analysis was deemed inappropriate due to heterogeneity in study designs, methods, and settings. A harvest plot (Ogilvie et al., 2008) was populated by extracted study data and used to assess weight of evidence. Each study was represented in the harvest plot by a bar and was grouped by health outcome: grey bars represented studies using bivariate, Chi-squared, or t-tests in analyses; black bars represented studies using multivariate or logistic analysis; short bars represented cross-sectional studies; medium-height bars represented case-control studies, and tall bars represented longitudinal or cohort studies. Statistically significant health benefits were those reported as significant at the $p \leq 0.05$ level in bivariate, multivariate, or chi-squared analyses. Assessed rigor scores were displayed above the study bar and studies were ordered by study rigor and design.

In the narrative synthesis, extracted findings on health outcomes were grouped by study rigor. Health findings from all rigorous studies were included in the narrative synthesis, and key health findings from less rigorous studies were included. Extracted findings from all papers on mediating factors including water source type, quality, quantity, storage, reliability, and distance to source were grouped by topic. Tables were populated by extracted data and sums were calculated using Microsoft Excel (Microsoft Corporation, 2011).

Results

Search results

The original search yielded 2,857 studies and an additional 745 studies were retrieved in January 2016 for a total of 3,602 studies (Figure 2). Twenty-two studies met the inclusion criteria and 10 additional studies were identified from bibliographies, resulting in 32 studies included in the review.

[Figure 2]

Study characteristics

The included studies contained 24 findings on diarrheal diseases, six on helminth infections, four on hepatitis A, four on child height, four on respiratory disease, three on skin infections, and one each on child weight, child weight-for-height, and trachoma. Eight studies reported multiple health outcomes included in the review (Checkley et al., 2004; Henry, 1981; Mason et al., 1986; Mukalay et al., 2010; Rajasekaran et al., 1977; Ryder et al., 1985; Thomas et al., 2016; Wang et al., 1989). Study design varied across health outcomes (Table 3). Studies were conducted in 24 countries and were concentrated in Sub-Saharan Africa, Southern Asia, developed regions, and Latin America and the Caribbean (Figure 3). Most studies were conducted in low- and middle-income countries; six were conducted in the United States. Over half of the studies (17) were conducted in rural areas; eight studies were conducted in urban and peri-urban areas, four were conducted in both urban and rural areas, and three did not report the setting (Table 4). One study was published in French (Mukalay et al., 2010); the remaining 31 were published in English.

[Table 3, Figure 3, Table 4]

Seventeen studies were rigorous (meeting 6 or more rigor criteria); all rigorous studies adjusted for or assessed the confounding effects of socioeconomic effects except two conducted in rural United States (Bulkow et al., 2012; Thomas et al., 2016). Eight of 15 less rigorous studies assessed effects of socioeconomic status in the analysis. Thirteen studies had durations of a year or longer, nine of which were rigorous (Aluisio et al., 2015; Bukenya et al., 1991; Bulkow et al., 2012; Checkley et al., 2004; Devoto et al., 2011; Molbak et al., 1997; Thomas et al., 2016; van der Hoek et al., 2001; van der Hoek et al., 2002). Common reporting omissions and sources of potential bias identified were non-systematic or non-representative participant selection, unadjusted statistical analysis, and non-disclosure of funding or conflict of interest (Table 5).

[Table 5]

Type of water source

Five studies investigated the health impacts of on-plot water sources other than piped connections, examining use of on-plot wells (Aluisio et al., 2015; Schemann et al., 2002; Stewart et al., 1955; van der Hoek et al., 2002; van der Hoek et al., 2001). Several diarrhea studies compared health effects of on-plot water supplies with multiple water sources types, such as public standpipes, wells, springs, and rivers. All other included studies used binary water variables in the analysis to compare households with on-plot and off-plot water supplies; some specified the water source types. Five studies investigated household use of multiple water sources; one reported exclusive use of the on-plot water source (Devoto et al., 2011), one reported rainwater as an alternative source (Dos Santos et al., 2015), and three reported use of multiple on- and off-plot sources (Brown et al., 2013; Henry, 1981; Wang et al., 1989).

Health impacts

Diarrheal diseases

Nineteen studies investigated diarrheal disease (Table 4) and reported 24 relevant findings: 13 statistically significant findings of lower risk of diarrhea among participants with on-plot water supplies; 9 findings of no significant effect; and two findings of significantly higher odds or prevalence of diarrhea associated with use of on-plot water supplies. Twelve findings were from rigorous studies and 12 were from less rigorous studies (Figure 4). Fourteen findings were on self-reported diarrhea of unknown etiology.

[Figure 4]

Among the ten rigorous studies on self-reported diarrhea, five studies found a significant association between on-plot water supplies and lower risk of diarrhea (Brown et al., 2013; Bukenya et al., 1991; Dos Santos et al., 2015; Molbak et al., 1997; van der Hoek et al., 2001). Households in Vietnam with on-plot water supplies had significantly lower longitudinal diarrhea prevalence than households with access to improved sources off plot (longitudinal prevalence ratio (LPR)=0.59, 95% CI: 0.39-0.91 ($p=0.018$)) (Brown et al., 2013). In Pakistan, odds of diarrhea were significantly higher for individuals lacking on-plot water supplies than for individuals with on-plot water (OR=1.52, 95% CI: 1.12-2.05) (van der Hoek et al., 2001). A study in Guinea-Bissau found significantly higher incidence of diarrhea among children from households using protected (rate ratio (RR)=1.28, 95% CI: 1.07-1.54) and unprotected (RR=1.42, 95% CI: 1.09-1.85) water supplies off plot compared to children from households using protected sources on-plot; household use of unprotected sources on-plot was also associated with significantly higher incidence than use of protected sources on-plot (OR=1.51, 95% CI: 1.18-1.94; overall trend $p=0.003$) (Molbak et al., 1997). Children from households lacking on-plot water supply in Papua New Guinea had significantly higher diarrhea incidence compared to children from households with on-plot supply (incidence density ratio (IDR)=1.56, 95% CI: 1.25-1.87, $p<0.01$) (Bukenya et al., 1991). Households with on-plot water access in Burkina Faso had lower odds of child diarrhea than households collecting water from sources between 5-30 minutes away (OR=0.57, $p<0.10$), but significantly lower odds of diarrhea than households with over 30-minute collection time

(OR=1.29, p<0.01) (Dos Santos et al., 2015).

Five rigorous studies reported no significant effects of on-plot access on diarrhea, but results were indicative of the importance of water availability. Children in a peri-urban community in Peru with the worst water and sanitation conditions (no on-plot water, small water storage containers, lack of sewerage) experienced 2% higher risk of diarrhea (95% CI: 1.00-1.04, p=0.057) than children with the best conditions (on-plot water, large water storage containers, sewerage); however, risk of diarrhea was not significantly different between households with on-plot sources and households using standpipes or cisterns (hazard ratio (HR)=1.09, 95% CI: 0.60-1.98) or neighbors' water source (HR=1.21, 95% CI: 0.96-1.52) (Checkley et al., 2004). Children from households in Afghanistan lacking water on-plot were found to have higher risk of diarrhea than children from households with on-plot access in the univariate analysis, but not the multivariate analysis (HR=1.08, 95% CI: 0.95-1.23, p=0.239) (Aluisio et al., 2015). Findings from studies in Brazil and Malaysia were suggestive of an association between access to indoor on-plot water supply and diarrhea, but not significant ((p=0.08) (Fuchs and Victora, 2002) (OR=1.73, 95% CI: 0.58-5.17) (Knight et al., 1992)). In urban Morocco, children and adults in households who gained access to on-plot water did not experience significant changes in diarrhea incidence compared to the control group, who used public taps, neighbors' taps, informal connections, or other water sources (RR=0.84, p>0.05) (Devoto et al., 2011). The analysis controlled for distance to the public tap and quantity of water consumption at baseline (Devoto et al., 2011). The authors suggested that the intervention did not have a significant impact on diarrhea outcomes because households already had access to water from neighbors' taps and public taps nearby, which exhibited similar water quality to on-plot household connections (Devoto et al., 2011).

Evidence from rigorous studies was divided on the effects of on-plot water access on self-reported diarrhea, but many studies reporting no significant effect had suggestive findings, indicating a possible relationship between diarrhea and on-plot water access. Three of four less rigorous studies on self-reported diarrhea found a significant health benefit from having on-plot water.

Few studies analyzing diarrheal etiology were found. One rigorous study found that use of on-plot water was not associated with giardiasis or cryptosporidiosis (Checkley et al., 2004). Among less rigorous studies, use of on-plot water was associated with lower incidence and prevalence of shigellosis among children (p<0.05) (Hollister et al., 1955; Rajasekaran et al., 1977; Stewart et al., 1955; Watt et al., 1953) and lower cholera incidence (p=0.02) (Wang et al., 1989). On-plot water access was not associated with prevalence of campylobacteriosis among children (Molbak et al., 1988) or household dysentery incidence (Wang et al., 1989). In two of the less rigorous studies not reporting a health benefit, children from households with on-plot water sources had significantly higher giardiasis and diarrhea prevalence than children from households using shared sources (p<0.001, p<0.05), but the statistical analyses were conducted by chi-squared tests and did not account for factors such as sanitation, hygiene, water source type, and water quality (Ryder et al., 1985; Mason et al., 1986).

Height, weight, and weight-for-height

Findings from the few studies that investigated child height and weight outcomes indicate that on-plot water supplies may be associated with greater height-for-age and weight-for-height but has no relationship to weight-for-age (Henry, 1981; Mukalay et al., 2010). All but one of the studies (Henry, 1981) on child height and weight either adjusted for or assessed effects of socioeconomic status in their analyses.

Evidence from two rigorous studies suggests a possible relationship between access to on-plot water and height-for-age. Children from households with on-plot water supplies and storage in Pakistan were found to be less likely to be stunted (low height-for-age) than children using off-plot supplies in the partial model where water, sanitation, and hygiene factors were analyzed separately in adjusted analyses (OR=3.28, 95% CI: 1.12-9.58), but there was no significant difference in the full model jointly analyzing water, sanitation, and hygiene (van der Hoek et al., 2002). However, children with on-plot water but lacking water storage were significantly more likely to be stunted than those children with on-plot water and storage in the full model (OR=2.95, 95% CI: 1.08-8.03), indicating that continuous water availability was associated with greater height-for-age (van der Hoek et al., 2002). In Peru, children with on-plot water were 0.6 cm taller than children lacking on-plot water, however the result was marginally significant (95% CI: -0.1-1.4 cm) (Checkley et al., 2004).

A less rigorous study in the Democratic Republic of Congo found that children lacking on-plot water were significantly more likely to be stunted than children with on-plot water (OR=1.5, 95% CI: 1.1-1.9 ($p=0.006$)), but did not differ significantly in weight-for-height (Mukalay et al., 2010). Similarly, in a less rigorous study in St. Lucia, children with on-plot water supplies had significantly greater height-for-age than children using public taps ($p<0.05$) but did not differ in weight-for-age (Henry, 1981). However, children with on-plot water had significantly higher mean growth increments (kg) between ages 3-6 months ($p<0.05$) (Henry, 1981).

Trachoma, scabies, impetigo, and respiratory infection

One rigorous trachoma study reported significantly improved outcomes for households with on-plot water supplies. Households with on-plot water in Mali experienced significantly lower risk of active trachoma (OR=0.76, 95% CI: 0.68-0.86, $p<0.001$) and intense trachoma (OR=0.73, 95% CI: 0.55-0.96 ($p=0.0025$)) than households lacking indoor, on-plot water supplies (Schemann et al., 2002).

Two studies reported associations between on-plot water access and lower risk of skin infections. In rural Alaska, one rigorous study found that skin infections decreased by 20% (95% CI: 10-30%, $p=0.003$) across four villages after installation of on-plot water access (Thomas et al., 2016). A less rigorous study conducted in Panama found that incidence of impetigo and scabies was significantly lower among children from households with on-plot water than from households collecting water from a stream

($p<0.05$); however, the study analysis did not account for confounders (Ryder et al., 1985).

Findings suggest lower risk of skin infections among households with on-plot water access, but findings on respiratory infection were mixed. One rigorous study reported that respiratory infections significantly decreased across four villages after installation of piped water access (16%, 95% CI: 11-21%, $p<0.0001$) (Thomas et al., 2016). Risk of respiratory infection was not significantly different between households with and without on-plot access in a second rigorous study (OR=0.64, 95% CI: 0.37-1.12, p=0.117) (Bulkow et al., 2012) and two less rigorous studies (Ryder et al., 1985; Singleton et al., 2003). In two studies reporting no effect, cases were defined by hospitalization with respiratory disease, and were found to be statistically more likely to be premature (Bulkow et al., 2012; Singleton et al., 2003) or high-risk infants (Bulkow et al., 2012), which could limit comparability between case and control status.

Hepatitis A

Evidence on health effects of on-plot water access on hepatitis A was divided and lower quality. Findings from two of four studies on hepatitis A suggest potential health benefits from on-plot water supplies. No rigorous studies were found for hepatitis A. Children in Egypt lacking on-plot water were 3 times more likely to have hepatitis A virus (HAV) antibodies than children using on-plot water supplies (OR=3.0, 95% CI: 1.1-10.2 ($p<0.01$)), and in China, seroprevalence of HAV was 73% lower in households with on-plot water than households who collected surface water ($p<0.001$) (Salama et al., 2007; Wang et al., 1989).

Helminth infections

Three rigorous studies found statistically significant health benefits from on-plot water supplies on helminth infections (Traub et al., 2004; Steinmann et al., 2010; Nasr et al., 2013). In India, individuals lacking on-plot water supplies had nearly twice the odds of *Trichuris trichiura* infection than individuals with on-plot water (OR=1.9, 95% CI: 1.2-2.6 (p=0.0122)), but odds of hookworm and *Ascaris lumbricoides* infections were not significantly different between households with and without on-plot water (Traub et al., 2004). A study in Malaysia reported that children lacking on-plot water supplies had significantly higher odds of *Trichuris* infection (OR=2.9, 95% CI: 1.9-4.5 ($p<0.001$)), *Ascaris* infection (OR=2.2, 95% CI: 1.4-3.2 ($p<0.001$)), and hookworm infection (OR=1.7, 95% CI: 1.1-2.9 (p=0.032)) than children with on-plot water (Nasr et al., 2013). Children with on-plot water supplies in Kyrgyzstan experienced significantly lower odds of *Ascaris* than children using shared ring-wells, a borderline significant finding (OR=0.56, p=0.057) (Steinmann et al., 2010). On-plot water supplies were not significantly associated with prevalence of *Enterobius vermicularis* or *Dicrocoelium dendriticum* in this study (Steinmann et al., 2010). Overall, findings indicated an association between on-plot water access and lower risk of helminth infection. Proposed mechanisms for health benefits varied in each paper: Traub et al. (2004) suggested health gains from improved water availability for hygiene; Nasr et al. (2013)

indicated higher water quality; and Steinmann et al. (2010) did not comment on a health mechanism.

Distance to source and collection time

Distance to household water sources was analyzed in three included studies. Prevalence of trachoma increased with distance to water source in Mali, although it was unclear if distance to source was measured or reported by study participants (Schemann et al., 2002). Odds of diarrhea were significantly lower among households with on-plot access compared to households with walk times between 5-30 minutes to source ($p<0.10$) and over 30 minutes ($p<0.01$), but odds of diarrhea were not significantly different among households with walk times under 5 minutes and between 5-30 minutes (Dos Santos et al., 2015). Households using public taps in Morocco had average distance of 112 m to their water source at baseline and spent 7.2 hours per week collecting water, but collection time and distance were not analyzed as risk factors for diarrhea (Devoto et al., 2011).

Water quantity, storage, and reliability

Six studies analyzed the relationship between on-plot water access and water quantity. Quantity of water use was estimated by metered water use (Brown et al., 2013; Thomas et al., 2016), user estimates (Brown et al., 2013; Schemann et al., 2002), household logs (Thomas et al., 2016), number of filled containers (Henry, 1981), or unreported methods (Devoto et al., 2011; Ryder et al., 1985). Five studies found that households with on-plot water supplies used greater quantities of water (Brown et al., 2013; Henry, 1981; Ryder et al., 1985; Thomas et al., 2016) and greater quantities for hygiene (Devoto et al., 2011). An inverse relationship between distance to source and quantity of water used was reported in Mali (Schemann et al., 2002). Prevalence of trachoma decreased progressively with increasing quantities of water used for face washing; statistical significance was not reported (Schemann et al., 2002). Households using between 20-50 L of water per capita per day experienced lower odds of diarrhea than households using under 10 L per capita per day in Burkina Faso (OR=0.70, $p<0.01$) (Dos Santos et al., 2015).

Three studies investigated size of water storage containers; children from households using small water storage containers such as pots, pans, and buckets were 0.8 cm (95% CI: 0.4-1.6) shorter than users of medium or large water containers such as drums or cisterns (Checkley et al., 2004). Households in Pakistan with a water connection and storage (mostly overhead tanks) used 48-113 L of water per capita per day, whereas connected households lacking storage had intermittent supply and used 16-29 L per capita per day (van der Hoek et al., 2002). Non-connected households used 10-15 L per capita per day (van der Hoek et al., 2002). Water storage and connections were analyzed jointly in the study analyses (van der Hoek et al., 2002; van der Hoek et al., 2001). Storing water in uncovered containers was associated with significantly higher odds of diarrhea compared to covered storage in one study (OR=1.79, $p<0.05$) (Dos Santos et al., 2015).

Reliability of piped on-plot water was investigated in a study in rural China; residents had to use surface water during periods of intermittent service, and length of time without water supply was significantly correlated with increased incidence of acute watery diarrhea ($p<0.001$) (Wang et al., 1989).

Water quality

Water quality was analyzed in 10 studies: 8 reported on diarrheal disease and one each reported on child height and scabies. Eight studies used *E. coli*, fecal coliform, and/or total coliform counts to assess water quality and two studies did not describe the water quality test (Hollister et al., 1955; Watt et al., 1953). On-plot water supplies had less microbial contamination than improved and unimproved off-plot sources (Brown et al., 2013) and surface water collected off-plot (Wang et al., 1989); one reported the difference was statistically significant (Brown et al., 2013). The studies suggested water quality differences between sources, but one study sampled water stored in the household (Brown et al., 2013) and sampling procedures in the second were unclear (Wang et al., 1989). One study did not analyze differences between water sources (Knight et al., 1992) and the remaining seven studies found similar levels of contamination across on- and off-plot supplies (Devoto et al., 2011; Bailey and Archer, 2004; van der Hoek et al., 2001; Ryder et al., 1985; Rajasekaran et al., 1977; Hollister et al., 1955; Watt et al., 1953), including surface water (Bailey and Archer, 2004; Ryder et al., 1985; van der Hoek et al., 2001). Three additional studies including surface water in the referent group to on-plot access did not report water quality (Fuchs and Victora, 2002; Mason et al., 1986; van der Hoek et al., 2002). Two studies reported that households with on-plot water sources stored water in containers, where it was contaminated (Ryder et al., 1985; Rajasekaran et al., 1977).

Three studies analyzed relationships between quality of water supply and health outcomes. Microbial water quality of household drinking water and water source was not associated with diarrheal disease in one rigorous study (Knight et al., 1992). In a second rigorous study, quality of water supply source was significantly associated with risk of diarrhea only among households with good water availability (on-plot water supply and storage) and toilets; quality of water supply source was not associated with risk of diarrhea among households with poor water availability (no on-plot water supply and storage), with or without toilets (van der Hoek et al., 2001). A less-rigorous study using water source type as a proxy indicator for quality (well or city water) found no statistical difference in shigellosis incidence between users of the water source types (Stewart et al., 1955).

Discussion

Our findings show that on-plot water sources are associated with lower prevalence of helminth infections. The impact of on-plot water supplies on diarrhea and height-for-age was weak in the pooled results but suggestive. On-plot water access appears associated with lower incidence of shigellosis, but the evidence quality is low. Results from few studies reported that on-plot water supplies are associated with lower risk of trachoma, skin infections, and cholera. On-plot water supplies were not associated with lower risk of giardiasis, cryptosporidiosis, or weight-for-age.

The findings are supported by previous reviews, which have reported lower prevalence of diarrhea, helminth infections, and trachoma due to improved water access (Esrey et al., 1991; Fewtrell and Colford, 2005; Strunz et al., 2014). Continuous supply, water quality, and storage emerged as mediating factors for health benefits of piped on-plot water, consistent with recent review findings (Wolf et al., 2014). A recent multi-country study found differences in water quality by water source type (Evans et al., 2013), but included studies reported little data on water quality by source type. Few studies analyzed distance to source in this review, which has been associated with child diarrhea, height, weight, and weight-for-age outcomes (Pickering and Davis, 2012). Meta-analyses have found that shorter distance to water source is associated with lower risk of diarrheal disease (Wang and Hunter, 2010) but not trachoma (Stocks et al., 2014); however, the trachoma meta-analysis contained many low-quality studies. One included study reported an inverse relationship between trachoma prevalence and distance to source (Schemann et al., 2002).

It has been suggested that the quantity of water used by households is inversely related to distance to water source beyond 1 km from the household (White et al., 1972; Cairncross and Cliff, 1987; Evans et al., 2013), but there was insufficient data to evaluate that relationship in this review. The effect of proximity to water source on quantity of water used (White et al., 1972; Tonglet et al., 1992; Evans et al., 2013) and allocation for hygiene (Thompson et al., 2001; Cairncross and Cliff, 1987) was observed; studies reported that households with on-plot water supplies used more water and allocated more water to hygiene behavior than households using off-plot sources. Households using greater quantities of water for hygiene experienced lower trachoma prevalence, as found in a recent review (Stelmach and Clasen, 2015).

Water quality was infrequently reported in included studies and could contribute to the health benefits of on-plot water. Two studies found that on-plot supplies had significantly better water quality than off-plot sources, but it was unclear whether contamination was introduced at the source or through collection, handling, or storage. Several studies used binary categorization of water sources as on- or off-plot and included surface water and unimproved sources in the referent off-plot group, which aggregates improved and unimproved source types that can vary in contamination (Bain et al., 2012) and accessibility. However, leaking pipes and intermittent service can compromise the quality of piped water (Kumpel and Nelson, 2014), and fecal contamination of piped water is frequent in low- and middle-income countries, particularly in rural areas (Bain et al., 2014a; Christenson et al., 2014). Additionally, several included studies reported that water obtained on plot was stored in containers and subsequently contaminated; this was reported in a recent study in Cambodia, which also found that water collected on-plot was frequently stored in the same container with water from unimproved sources (Shaheed et al., 2014). Measured water quality was not associated with diarrhea except in households with on-plot water supply, water storage, and toilets (van der Hoek et al., 2001). Results support previous assertions that water quality may have greater impact among households with better water, sanitation, and hygiene conditions (VanDerslice and Briscoe, 1995; Esrey, 1996).

Water quality has a role in transmission of diarrheal diseases that can be waterborne (Clasen et al., 2007). On-plot water access may have differential impacts on diarrheal diseases arising from multiple transmission routes and pathogens of relative infectivity (White et al., 1972; Esrey et al., 1985). Many waterborne pathogens can be transmitted through both waterborne and water-washed routes (Bradley, 1977; Kolsky, 1993), both of which may be modified by on-plot water availability. Also, the probability and type of water contamination can differ by water source type. Use of on-plot water supplies was not associated with decreased odds or prevalence of the protozoal infections giardiasis and cryptosporidiosis, diseases with high infectivity (Esrey et al., 1985). While it was associated with lower cholera incidence (low infectivity), it was also associated with lower incidence and prevalence of shigellosis – normally thought of as having higher infectivity. The dual water-washed and waterborne nature of certain pathogens may partially account for apparent inconsistencies in the evidence. Diseases typically considered water-washed and more associated with hygiene behavior than water quality, such as trachoma, scabies, and shigellosis (White et al., 1972; Esrey et al., 1985), were less prevalent in households with on-plot water supplies. Most of the included studies on self-reported diarrhea did not analyze diarrheal etiology, and the differential impact of on-plot water supplies on specific diarrheal pathogens may account for some of the variation in study findings.

Infrastructure for on-plot water access can introduce health risks. Diseases transmitted through water-related insect vectors may be propagated by poor drainage of domestic wastewater (Knudsen and Slooff, 1992) or leaking pipes (Dua et al., 1997), and water sources on-plot localize these health risks near the household. Conversely, households with on-plot water access may have reduced exposure to standing rainwater and community wastewater, which is often localized near the tap in communities with poor drainage services.

A major confounding factor in the comparison of households with on- and off-plot water supplies is socioeconomic status. Inequalities in access to piped water have been linked to wealth and urban residence (Yang et al., 2013; WHO/UNICEF, 2012). While all rigorous studies analyzed socioeconomic indicators, socioeconomic effects may be difficult to accurately represent in statistical analysis, which could result in an overestimation of the effect size of on-plot water supplies.

Limitations of this review include the small number of studies retrieved for health outcomes, limiting the generalizability of review findings. Qualitative and secondary data analyses were excluded from the review and could provide more evidence on the impacts of on-plot water supplies on health and well-being. Conducting the search in English likely caused bias in results, as most studies were conducted in South Asia, Sub-Saharan Africa, developed countries, and Latin America and the Caribbean. Although included studies were distributed across geographic regions, rural settings were more highly represented in the review than urban and peri-urban settings. Studies from different regions may not be comparable due to differences in geography, climate, or culture. Studies were not globally representative, with only three studies from China and India, and participant age ranges varied by study. Effect measures were not estimated for health outcomes due to heterogeneity in study designs and settings.

The most common methodological flaw identified in the rigor assessment was unclear, non-systematic, or non-randomized participant selection. Several studies recruited participants from health clinics, hospitals, and schools, which may have undefined catchment areas with different population groups, limiting comparability of study participants. Many older and less rigorous studies did not use multivariate regression and did not adjust for individual factors such as age, socioeconomic status, or sanitation access. Additionally, several studies did not report the time and duration of the study, which are important factors for studies on diarrheal diseases since they are subject to seasonal effects (Jagai et al., 2012) and seasonality is known to affect source water quality and choice of source (Kostyla et al., 2015).

Little evidence was found to disentangle the roles of water quality, water quantity, distance to water source, and hygiene behavior from the benefits of on-plot water supplies. Most studies did not collect or report observational data on water use, use of multiple water sources, or use of non-piped sources on premises. Data collection and improved reporting on water source location, water quality, and water treatment would better indicate whether health benefits from on-plot access arise from improved water quality, accessibility, or both. Additionally, a few studies reported intermittent service and storage of water from on-plot sources, which could reduce potential health gains from on-plot water access. Rigorous research is needed to characterize health impacts of on-plot water access considering water source accessibility and reliability, use of multiple sources, household water storage, and quantity of domestic water use. Health benefits from on-plot access may be constrained by any of these factors, and little research examines them holistically. Such research could provide clearer evidence for levels of water service encompassing domestic water quantity, reliability, and accessibility (Kayser et al., 2013). Household water access and health are intimately connected, and more focused research into household water supplies and water use would provide clearer evidence for the health and other impacts of on-plot water supplies.

On-plot water supplies provide opportunity for household health benefits, but access to this level of service remains limited; globally, piped on-plot water access is concentrated in urban areas (WHO/UNICEF, 2013). In 2015, an estimated 2.35 billion people lack access to on-plot water supplies (Cumming et al., 2014) and their reported health benefits. Policies promoting and facilitating on-plot access with continuous service may reduce disease and extend health benefits to larger populations. Given the impacts of on-plot water access on child diarrhea, helminth infections, and growth, such policies would have beneficial long-term health implications for children (Moore et al., 2001). Policies promoting increased access to on-plot water supplies would complement the universal safe water access target of the Sustainable Development Goals by furthering the goals of progressive realization of the human right to safe water (WHO/UNICEF, 2013), increasing water service levels, and propagating household health benefits.

Conclusions

On-plot water access results in fewer helminth infections, less diarrhea, and greater child stature. Limited findings suggest that use of on-plot water supplies has a stronger impact on water-washed diseases than waterborne diseases. Review findings suggest that self-reported diarrhea obscures the differential impact of on-plot water access on different diarrheal pathogens.

There are substantive gaps in research literature. Few studies investigated household use of multiple water sources or differentiated the effects of water quality and quantity on health outcomes. More comprehensive studies examining water access and use are needed to elucidate the roles of water and hygiene behavior in health, enabling clearer and more accurate guidelines for water policy, interventions, and service delivery.

The review findings indicate that on-plot water access is a meaningful indicator for examining water-related health outcomes and a useful benchmark for the Sustainable Development Goal water target and the human right to safe water. Promoting progressive realization of on-plot water access would improve household water access and deliver benefits to health and well-being where water is predominantly collected from sources located off-plot.

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