Pit Latrines and Their Impacts on Groundwater Quality: A Systematic Review

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BACKGROUND: Pit latrines are one of the most common human excreta disposal systems in low-income countries, and their use is on the rise as countries aim to meet the sanitation-related target of the Millennium Development Goals. There is concern, however, that discharges of chemical and microbial contaminants from pit latrines to groundwater may negatively affect human health.

OBJECTIVES: Our goals were to a) calculate global pit latrine coverage, b) systematically review empirical studies of the impacts of pit latrines on groundwater quality, c) evaluate latrine siting standards, and d) identify knowledge gaps regarding the potential for and consequences of groundwater contamination by latrines.

METHODS: We used existing survey and population data to calculate global pit latrine coverage. We reviewed the scientific literature on the occurrence of contaminants originating from pit latrines and considered the factors affecting transport of these contaminants. Data were extracted from peer-reviewed articles, books, and reports identified using Web of ScienceSM, PubMed, Google, and document reference lists.

DISCUSSION: We estimated that approximately 1.77 billion people use pit latrines as their primary means of sanitation. Studies of pit latrines and groundwater are limited and have generally focused on only a few indicator contaminants. Although groundwater contamination is frequently observed downstream of latrines, contaminant transport distances, recommendations based on empirical studies, and siting guidelines are variable and not well aligned with one another.

CONCLUSIONS: In order to improve environmental and human health, future research should examine a larger set of contextual variables, improve measurement approaches, and develop better criteria for siting pit latrines.

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An estimated 2.6 billion people lack access to improved sanitation—defined as facilities that hygienically separate human excreta from human contact (World Health Organization (WHO)/UNICEF 2010). Improved sanitation includes water-based toilets that flush into sewers, septic systems, or pit latrines; simple pit latrines; and ventilated improved pit latrines. There is strong evidence that access to improved sanitation can reduce diarrhoea morbidity and mortality as well as soil-transmitted helminths (Albonico et al. 2008; Cairncross et al. 2010b).

The United Nations (UN), through the Millennium Development Goals, has set a target of halving by 2015 the proportion of the population without sustainable access to improved sanitation (WHO/UNICEF 2012c). To achieve this target, approximately 1 billion people in urban areas and 900 million people in rural areas must gain access to improved sanitation by 2015 over the baseline year, 1990 (WHO/UNICEF 2012c). In low-income countries [with a gross national income per capita of ≤ US$1,025 (World Bank 2013)], many households use improved or unimproved pit latrines because of their low cost and availability (Cairncross et al. 2010a; Jain 2011). Improved pit latrines are the most basic and inexpensive form of improved sanitation. They typically consist of a pit—circular, rectangular, or square—dug into the ground and covered with a concrete slab or floor with a hole through which excreta falls. Unimproved pit latrines are those without slabs or platforms.

In concert with sanitation goals, the UN has also set explicit targets to increase the proportion of the global population using an improved drinking-water source (WHO/UNICEF 2012c). In the context of low-income countries, water from improved sources is frequently derived from groundwater via protected springs, protected dug wells, tube wells, and boreholes (UN 2008). Thus, the use of groundwater (which typically receives no subsequent treatment to improve quality) for drinking water supplies is increasing dramatically (Rosa and Clasen 2010). Because of the increasing uses of both pit latrines and groundwater resources in low-income countries, there is concern that pit latrines may cause human and ecological health impacts associated with microbiological and chemical contamination of groundwater. Pit latrines generally lack a physical barrier, such as concrete, between stored excreta and soil and/or groundwater (van Ruyenved and Fourie 1997). Accordingly, contaminants from pit-latrine excreta may potentially leach into groundwater, thereby threatening human health through well-water contamination. In this study, we assessed the known and measured environmental health impacts associated with groundwater contamination by pit latrines. In particular, we a) calculated global pit latrine coverage, b) systematically reviewed empirical studies of the impacts of pit latrines on groundwater quality, c) evaluated latrine siting standards, and d) identified knowledge gaps regarding the potential for and consequences of groundwater contamination by latrines.

Methods

Global pit latrine coverage. We used existing survey data to estimate the percentages of people per country who a) use pit latrines for sanitation, b) do not have any sanitation facilities, and c) use groundwater sources for drinking water (see Supplemental Material, Table S1 [http://dx.doi.org/10.1289/ehp.1206028]).

Data from the most recent reports for each country were obtained from Demographic and Health Surveys (USAID 2012), Multiple Indicator Cluster Surveys (UNICEF 2012), and China’s Economic, Population, Nutrition, and Health Survey (WHO/UNICEF 2012a, 2012b). We included improved latrines (flush toilets and toilets that pour/flush to pit latrines (water is poured by hand for flushing), ventilated improved latrines, and pit latrines with slabs) and unimproved latrines (traditional latrines, pit latrines without slabs, and shared latrines) when estimating pit latrine use (see Supplemental Material, p. 2, for definitions of types of sanitation). Composting toilets, considered improved facilities, were not included in our analysis, nor were sanitation facilities for which final disposal of human excreta is unknown (e.g., hanging latrines and bucket latrines). For estimates of the proportions of improved versus unimproved latrines, we assumed that unspecified latrines were split evenly between improved and unimproved. Data for people without a sanitation facility include “no facility” and “open defecation

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that must be addressed in order to make better-terms of siting guidelines for pit latrines and pit latrines. By synthesizing existing results in measure of risk associated with the presence of contaminants from pit latrines or studies we more fully characterized the studies that contaminated latrines or pit latrines without slabs). The number of users per latrine varies by locale, but based on the excreta production rates of Feacham et al. (1983), globally per day, as much as 2.1 billion kilograms of urine and 0.6 billion kilograms of feces are deposited into latrines. In the countries where pit latrines are prevalent (see Supplemental Material, Table S1), > 2 billion people depend on groundwater for their primary drinking water supply.

These calculations are among the first estimates of the numbers of people using pit latrines and groundwater in low-income countries. Because some national survey data are several years old, estimates have a fair degree of uncertainty at the country level. However, our estimate for the total number of people without any sanitation facility (1.11 billion) is in agreement with the independently calculated Joint Monitoring Program 2010 estimate for open defection (1.1 billion people) (WHO/UNICEF 2012c), which suggests that our approximations may be more robust at the global level. In addition, our estimate of the total 2010 population for countries included in this analysis (5.22 billion) is consistent with the UN population estimate for “less developed regions” (or “all regions of Africa, Asia (excluding Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia”) of 5.66 billion (UN 2011).

Results

Global pit latrine coverage. Globally, there is great variability in latrine coverage. We estimate that approximately 1.77 billion people around the world use some form of pit latrine as their primary means of sanitation [Figure 1; see also Supplemental Material, Table S1 (http://dx.doi.org/10.1289/ehp.1206028)]. In addition, we estimate that 48% of people using pit latrines used facilities characterized as improved, whereas the remainder uses shared or unimproved facilities (e.g., traditional latrines or pit latrines without slabs). The number of users per latrine varies by locale, but based on the excreta production rates of Feacham et al. (1983), globally per day, as much as 2.1 billion kilograms of urine and 0.6 billion kilograms of feces are deposited into latrines. In the countries where pit latrines are prevalent (see Supplemental Material, Table S1), > 2 billion people depend on groundwater for their primary drinking water supply.

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Studies on groundwater contamination from pit latrines. Twenty-four studies directly assessed the transport of contaminants or applied statistical methods to estimate a measure of risk associated with the presence of pit latrines (Table 1); these studies assessed either chemical contaminants (4 studies), microbial contaminants (2 studies), or both (18 studies). Human excreta are the main input to pit latrines, although other inputs may contribute significantly to pit contents depending on local practices [see Supplemental Material, Inputs to Pit Latrines, p. 3, for additional details (http://dx.doi.org/10.1289/ehp.1206028)]. Human feces harbor a large number of microbes, including bacteria, archaea, microbial eukarya, viruses, and potentially protozoa and helminths (see Supplemental Material, Table S2) (Feacham et al. 1983; Ley et al. 2006; Ramakrishna 2007). The largest chemical concerns from excreta disposed in on-site sanitation systems are considered to be nitrate [British Geological Survey (BGS) 2002; Faurie and Vannevel 1995; Pedley et al. 2006], phosphate (Faurie and Vannevel 1995), and chloride (BGS 2002) (see Supplemental Material, Table S3).

Microbiological contaminants associated with pit latrines. Concentrations of most fecal microorganisms decline after excretion, but these microorganisms may still impair ground-

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an alkaline alluvium soil, Dyer (1941) reported that movement of total coliforms was limited to < 7 m from the pit. A relatively short transport distance was also found in South Africa, where high fecal coliform counts (> 10 colony forming units (cfu)/100 mL) were detected only 1 m from a pit latrine (Still and Nash 2002). Dzwairo et al. (2006) found fecal and total coliform contamination greatly reduced > 5 m from pit latrines.

In a study of 12 pour/flush latrines, Banerjee (2011) found that transport of total and fecal coliforms increased during the monsoon period and in sandy soils. The author noted that the maximum travel distance of bacteria was 10 m from pits (Figure 2). In contrast, in a study in Zimbabwe, Chidavaenzi et al. (1997) found that groundwater contamination was higher in the dry season than in the wet season, with coliforms detected up to 20 m from a pit.

Nearly one-fourth of the studies analyzed associations between microbiological water quality in preexisting wells and factors such as proximity of pit latrines to assess latrine impacts on groundwater. At a study site in India characterized by a shallow water table and fractured rock aquifer, high concentrations of fecal coliforms were found in domestic wells located near pit latrines and septic tanks (Pujari et al. 2012). At a contrasting site, characterized by alluvial formations, the authors detected no or low levels of fecal contamination (Pujari et al. 2012). In a georeferenced spatial study of viral contamination, Verheyen et al. (2009) sampled 287 drinking-water sources (247 water wells, 25 pumps, and 15 surface water samples) proximate to 220 latrines. Adenoviral DNA was repeatedly detected in 26 water sources, and rotaviral RNA was detected in 1 source. In multiple rounds of sampling, 40 of the 287 drinking-water sources were positive for viral contamination at least once. Verheyen et al. (2009) found a significant positive association between viral contamination of a water source and at least 1 latrine within a radius of 50 m (Figure 2). These authors hypothesized that during the wet season, viruses were transported by groundwater flow in the upper part of the soil, whereas viral transport in the dry season was more likely a result of virus-contaminated surface water.

Associations between groundwater contamination and factors related to sanitation facilities are complicated by the co-occurrence of multiple contaminant sources, particularly when information on groundwater flow patterns is not available. A study of groundwater quality in an informal settlement of Zimbabwe found detectable total and fecal coliforms in more than two-thirds of study boreholes and existing domestic wells (Zingoni et al. 2005). The abundance of pit latrines, used in > 75% of the households, and the presence of informal trading areas within the settlement were likely sources of fecal pollution. The authors suggested that shallow wells

Figure 1. Percentage of low-income country populations using pit latrines as a primary sanitation facility (A) and groundwater as a primary drinking water source (B). Countries with no data presented were not included in the analysis.
and boreholes in the study area, as well as the incomplete lining of most latrines, contributed to high levels of groundwater contamination (Zingoni et al. 2005). In a study conducted in Moldova, Banks et al. (2002) concluded that groundwater pollution within villages was likely caused by latrines, livestock and stored manure, solid-waste landfills, and leakage from wastewater pits.

Even in areas with a high density of pit latrines, microbiological groundwater contamination may not necessarily be detected. Three studies found no strong positive association between poor bacteriological water quality and sanitary surveys or proximity to latrines (Ahmed et al. 2002; Howard et al. 2003; Tandia et al. 1999), although Ahmed et al. (2002) found fecal coliforms and streptococci in sediments 10 m below latrines.

Movement of bacteria from latrines is often limited by formation of a “scum mat,” which develops around the latrine pit and reduces the movement of fecal bacteria (BGS 2002; Caldwell 1937a). This mat (also referred to as a “biologically active layer,” “biolayer,” or “clogged” zone) enhances bacterial removal through filtration and predation by antagonistic organisms, but it may take several months to develop around new latrines (Caldwell and Parr 1937). In addition, clogging may result from blockage of soil pores by solids that have been filtered out, swelling of clay minerals, and precipitation of insoluble salts (Franceys et al. 1992). In a study testing liners as a way to reduce groundwater contamination from pit latrines, Nichols et al. (1983) found fecal coliforms in soil samples taken adjacent to only one of five peat-lined pits, compared with three of three unlined pits. The one peat-lined pit that showed contamination was located in shallow and rocky soil and was under saturated conditions.

### Chemical contaminants associated with pit latrines. Nitrate. Because of high concentrations of nitrogen in human excreta, its adverse impacts to human health, and its use as an indicator of fecal contamination, nitrate has been the most widely investigated chemical contaminant derived from pit latrines. Consumption of high concentrations of nitrate in drinking water is known to have serious health implications, including methemoglobinemia in infants, vomiting, diarrhea, and other gastrointestinal symptoms in children and adults. Nitrate is also a carcinogenic contaminant that has been linked to the development of cancer in humans and animals (WHO 2004).Nitrate is produced through the processes of nitrification and denitrification, which involve the conversion of ammonia to nitrate and nitrate to nitrogen gas, respectively. These processes are influenced by factors such as temperature, pH, and the presence of organic matter. In areas with high nitrate levels, groundwater may be unfit for human consumption without appropriate treatment, such as filtration or disinfection. To mitigate the risk of nitrate contamination, it is important to implement best management practices to reduce nitrate inputs to groundwater, such as the use of effective sanitation systems, proper manure management, and the use of riparian buffers. Compliance with national and international guidelines and standards is also crucial to ensure the safety of drinking water supplies.

### Table 1. Summary of selected studies that assessed groundwater or soil contamination associated with pit latrines.a

| Source          | Country         | No. of latrines in study | Experimental design | Subsurface conditions | Sampling time frame | Water quality parameters | Conclusions                                                                 |
|-----------------|-----------------|--------------------------|---------------------|-----------------------|---------------------|---------------------------|----------------------------------------------------------------------------|
| Vinger et al. 2012 | South Africa    | 15                       | Sampled existing wells | No data               | June–July           | Ammonia, nitrate, nitrite | Higher levels of contaminants observed at distances < 11 m from pit latrines |
| Pujari et al. 2012 | India           | 7                        | Sampled existing wells | Fine loamy silt, sandy loam, intermittent clay | Summer and monsoon seasons | Fecal coliforms, total dissolved solids, nitrate | No to low levels of nitrate and fecal coliforms observed |
| Banerjae 2011   | India           | 12                       | Installed test wells  | Saturated and unsaturated soils of gravel, sand, silt, clay, and laterite | Premonsoon and monsoon seasons | Total coliforms, fecal coliforms, chloride solution used as tracer | Movement of chloride tracers and coliforms limited to < 10.2 m from pits |
| Verheyen et al. 2009 | Benin          | 220                      | Sampled existing wells | No data               | Wet and dry seasons, 2003–2007 | Adenovirus, rotavirus | Viral contamination of groundwater associated with latrine proximity |
| Dzwairo et al. 2006  | Zimbabwe        | 3                        | Installed test wells  | Saturated and unsaturated sandy soils | February–May 2005 | Ammonia, nitrate, turbidity, pH, conductivity, total coliforms, fecal coliforms | Fecal coliform movement greatly reduced > 5 m from pits; all nitrate levels and 99% of ammonia levels met WHO drinking water standards |
| Zingoni et al. 2005 | Zimbabwe        | Not specified            | Sampled existing wells and installed test wells | No data               | No data               | Na, Zn, Cu, Co, Fe, phosphate, nitrate, total coliforms, fecal coliforms | Elevated levels of nitrate and coliform bacteria in most parts of study area |
| Mafa 2003       | Botswana        | Not specified            | Sampled existing wells | Fractured rock overlain by alluvial sediment, clay, sand, and weathered rock | July and August 2000 | Broad set of hydrochemical analyses | Elevated levels of nitrate in several zones where pit latrines were common |
| Banks et al. 2002 | Kosova, Moldova, Siberia | Not specified          | Sampled existing wells and springs | Highly variable: clay to sandy soils | 1996–2000           | Chloride, sulfate, potassium, nitrate | Elevated levels of nitrate likely from latrines |
| Howard et al. 2003 | Uganda          | Not specified            | Sampled protected springs | Highly variable: clay to sandy soils | Monthly, March 1998 through April 1999 | Fecal streptococci, fecal coliforms, nitrate | No significant relationship between microbiological contamination and pit latrine proximity |
| Still and Nash 2002 | South Africa    | 1                        | Installed test wells  | No data               | Bimonthly, 2000–2002 | Fecal coliforms, nitrate | Low levels of nitrate (< 10 mg/L) and fecal coliforms (10 cfu/100 mL) found > 1 m of latrine |
| Ahmed et al. 2002 | Bangladesh      | Not specified            | Sampled existing wells | Two aquifer systems, clay, silt, and fine to coarse sand | 2- to 8-week intervals, 1998–1999 | Fecal streptococci, fecal coliforms, broad set of hydrochemical analyses | Bacteriological water quality generally good (< 10 fecal coliforms/100 mL); water quality poorly correlated with sanitary surveys |
| Chidavaenzi et al. 2000 | Zimbabwe      | 2                        | Installed test wells  | Stratified fine-grain sandy soils | Wet and dry seasons | Nitrogen, coliforms | Rapid reductions in coliform, sulfate, and nitrogen levels within 5 m from pits; contamination present up to 20 m |

*Table continued*
groundwater nitrate concentrations near latrines were above local background levels, even if they remained below or near the WHO guideline (Baars 1957; Caldwell and Parr 1937; Chidavaenzi et al. 2000; Jacks et al. 1999; Zingoni et al. 2005).

High nitrate concentrations have been attributed to latrines through association and assumptions based on general proximity, but pinpointing the actual sources of nitrate in groundwater has proved challenging (WHO 2006). Nitrate may be derived from numerous potential sources in urban and rural environments, including latrines, plant debris, animal manure, garbage repositories, livestock pens, soil, and fertilizers (Girard and Hillaire-Marcel, 1997; Howard et al. 2002; Melian et al. 1999; Vinger et al. 2012); and nitrate can be formed and lost through natural soil processes (Jacks et al. 1999). Jacks et al. (1999) used mass-balance calculations to estimate that 1–50% of nitrogen leached to groundwater from latrines in Botswana. Although significant quantities of leached nitrate may have been lost to denitrification in poorly drained soils, the calculations suggested that nitrogen loss from latrines helped describe the high nitrate concentrations of groundwater (50 mg/L) in the area. The authors concluded that moving drinking wells outside of the habituated area would help avoid nitrate contamination of drinking water.

Girard and Hillaire-Marcel (1997) used nitrogen isotopes to determine the source of nitrate pin pointing the actual sources of nitrate in groundwater. They concluded that the isotope ratios were consistent with a leaching source of nitrate from latrines. This study suggests that nitrogen isotopes could be a useful tool for tracing the source of nitrate in groundwater.

### Table 1. Continued.

| Source          | Country       | No. of latrines in study | Experimental design          | Subsurface conditions                           | Sampling time frame | Water quality parameters | Conclusions                                      |
|-----------------|---------------|--------------------------|------------------------------|------------------------------------------------|--------------------|--------------------------|--------------------------------------------------|
| Jacks et al. 1999 | Botswana      | 4                        | Sampled existing wells       | Well-drained and poorly drained soils           | No data            | Phosphorous, nitrogen isotopic ratios, chloride   | Variable nitrate leaching from pit latrines       |
| Tandia et al. 1999 | Senegal      | Not specified            | Sampled existing wells       | Fine to coarse sand                             | July and November 1989 | Broad set of hydrochemical analyses, fecal coliforms | Nitrate contamination in water strongly correlated with latrine proximity |
| Nichols et al. 1983 | USA          | 8                        | Installed test wells         | 3 latrines on clayey soil; 3 on shallow loam; 2 on sand; all wells -drained | June and August 1975–1979 | Nitrate, phosphorus, fecal coliforms | Latrines with peat liners reduced movement of phosphorus and fecal coliforms but not nitrate. |
| Lewis et al. 1980 | Botswana      | 30 pit latrines in the study area | Sampled existing wells and test wells | Clayey soils and fissured rock | October 1977 through February 1978 | Broad set of hydrochemical analyses, E. coli, chloride solution used as tracer | Contamination of wells near latrine with E. coli and nitrate; rapid transport of chloride tracer |
| Baars 1957       | Netherlands   | Not specified            | Sampled soil and existing wells | Unsaturated sandy soils                         | September 1951 and January and March 1952 | Ammonia, E. coli, nitrate | Contamination in soil samples limited to < 1.5 m from latrines |
| Dyer 1941        | India         | 1                        | Installed test wells         | Saturated and unsaturated alkaline alluvium soils | December–September | Chloride, nitrate, total coliforms | Movement of total coliforms limited to < 7 m from pit |
| Caldwell 1938a   | USA           | 3                        | Installed test wells         | Fine gravel to clayey soils                     | May–November 1933  | Bacillus aerogenes, anaerobes, odor, pH, B. coli | B. coli movement limited to 3 m from pits |
| Caldwell 1938b   | USA           | 1                        | Installed test wells         | Fine gravel to clayey soils                     | November 1932–November 1933 | Nitrate, dissolved oxygen, chloride, nitrite, pH, odor, colon aerogenes group, B. coli, anaerobes | Limited movement of B. coli to 3 m from pit and chemicals to 24 m |
| Caldwell and Parr 1937 | USA       | 8 bored hole latrines    | Installed test wells         | Partially saturated fine gravel to clayey soils | May 1932–May 1933  | Nitrate, dissolved oxygen, chloride, nitrite, pH, odor, colon aerogenes group, B. coli, anaerobes | Movement of bacteria and chemicals to within 10 m and 26 m of latrine, respectively |
| Caldwell 1937b   | USA           | 1 envelope pit latrine   | Installed test wells         | Unsaturated fine gravel to clayey soils         | May–November 1933  | Colon aerogenes group, pH, odor, B. coli, anaerobes | Bacteria greatly reduced to within 2 m from pit |
| Caldwell 1937a   | USA           | 1                        | Installed test wells         | Saturated fine gravel to clayey soils           | August 1932–November 1933 | Colon aerogenes group, pH, odor, B. coli, anaerobes | Movement of bacteria to within 25 m of latrine |
| Kligler 1921     | USA           | 50                       | Sampled soil at varying distances | Unsaturated and sand, sandy clay, and clay | Wet and dry seasons, 1918–1919 | Colon aerogenes group, pH, odor, B. coli, anaerobes | Bacterial movement limited to < 5.5 m from pit |

Abbreviations: Co, cobalt; Cu, copper; Fe, iron; Na, sodium; Zn, zinc.

*Only studies that either directly assessed the transport of contaminants from pit latrines or studies that applied statistical methods to estimate a measure of risk associated with the presence of pit latrines are included. No specific data were provided on the density or number of pit latrines in the study area. Culture-based assays were used for all microbiological tests, except for Verheugen et al. (2009), who used genotyping methods.
nitrate pollution in a fractured rock aquifer of Niger. Due to fermentation of feces and ammonia volatilization in latrines, isotopic enrichment of residual matter creates a nitrate source that is isotopically distinguishable from nitrate of other sources. Nitrate concentrations in wells reached 11.6 milliequivalents/L, which may have been a consequence of contamination by latrines and deforestation (Girard and Hillaire-Marcel 1997). The authors cautioned that, given annual population growth rates and increased latrine densities, wells that had safe nitrate concentrations at the time of the study might become polluted in the future.

A more common approach in identifying nitrate sources has been to compare areas with similar environmental characteristics but different population and latrine densities. By analyzing water samples from installed boreholes in an informal settlement in Zimbabwe, Zimgoni et al. (2005) demonstrated that the highest nitrate concentrations in groundwater (20–30 mg/L) were associated with the highest population and latrine latrine densities of the settlement. In Siberia and Kosova, nitrate concentrations were sometimes > 100 mg/L in groundwater of villages with high latrine densities and minimal septic tanks, but concentrations were below hazardous levels in agricultural and unpopulated settings (Banks et al. 2002). Groundwater nitrate concentrations have also been correlated with proximity to pollution sources, including pit latrines, in Senegal and South Africa (Tandia et al. 1999; Vinger et al. 2012).

Environmental factors also play a role in governing groundwater pollution from latrines. Pujari et al. (2012) compared the impacts of on-site sanitation in two Indian megacities and concluded that hydrogeological conditions were strong predictors of the threat of nitrate contamination of well water; an area with shallow groundwater was more susceptible to pollution from latrines than an area with a deeper water table. In eastern Botswana, buildup of nitrogenous latex effluent in soils and subsequent downward leaching of nitrate appeared to promote dissolved nitrate concentrations > 500 mg/L in groundwater (Lewis et al. 1980); the authors concluded that the fissured bedrock aquifer allowed for rapid contaminant transport. Whereas soil type immediately below the pit is likely to influence the degree of nitrate transport (Caldwell and Parr 1937), associations with soil type have not always been observed (Nichols et al. 1983). In addition, in an area with high nitrogen loading from latrines but where groundwater was devoid of oxygen, nitrate concentrations were minimal, presumably because of denitrification (Ahmed et al. 2002).

Thus, both environmental conditions and human factors are major drivers of nitrate contamination from latrines, and the highest concentrations in well water are expected to be found downstream of areas with high latrine use (Chidavaenzi et al. 2000; Mafa 2003; Vinger et al. 2012). After nitrate is leached from latrines, a number of factors may control travel distance. Certain chemical contaminants may be transported farther than microbial contaminants because they are not as inhibited by the biolayer that commonly forms around latrines (Caldwell and Parr 1937).

Similarly, peat-lined pits were associated with reduced bacterial and phosphate transport from latrines but appeared to be ineffective in limiting nitrate (Nichols et al. 1983). In contrast, Chidavaenzi et al. (2000) estimated that the nitrogen influence from latrines extended only 5 m from the latrine source, whereas microbial contamination extended up to 20 m downstream. In a small study, Padmasiri et al. (1992) observed decreases in soil nitrate concentrations at 1.5 m from the latrine. Overall, although data are sparse, direct measurements and estimates of lateral transport distances for high levels of pit latrine-derived nitrate—where it has been detected—range from approximately 1 to 25 m (Caldwell 1938b; Caldwell and Parr 1937; Chidavaenzi et al. 2000; Lewis et al. 1980; Still and Nash 2002; Vinger et al. 2012) (Figure 2).

**Chloride.** After nitrate, chloride has been the most commonly investigated chemical indicator of groundwater contamination from latrines because of its high concentrations in excreta and its relative mobility in the subsurface. Although there are no known health risks from chloride in drinking water, concentrations > 250 mg/L may affect the taste and acceptability of water (WHO 2011). In a study from Botswana, Lewis et al. (1980) found the highest chloride concentrations in soils closest to latrines. In Bangladesh, dissolved concentrations reached 400 mg/L at shallow depths, but then decreased with depth and distance from latrines (Ahmed et al. 2002). Chloride is typically transported with minimal retention during groundwater flow, and concentrations frequently track with nitrate levels (Banks et al. 2002; Caldwell 1938b; Caldwell and Parr 1937; Jackets et al. 1999; Lewis et al. 1980; Tandia et al. 1999) unless subsurface conditions promote nitrate reduction (Ahmed et al. 2002). Variable distributions of latrine contaminants resulting from pumping and seasonal fluctuations have been demonstrated by studies using chloride salts as tracers (Banerjee 2011; Lewis et al. 1980).

**Ammonia.** Ammonia, derived either directly from latrine waste or following denitrification of nitrate released from latrines, has not been reported to accumulate appreciably in groundwater near latrines. In a study of three pit latrines, Dzwairo et al. (2006) observed only one incidence of ammonium (NH₄⁺) > 1.5 mg/L in well water that was microbiologically contaminated by latrines. In groundwater with latrine-derived nitrate concentrations that exceeded 500 mg/L, Lewis et al. (1980) found NH₄⁺ at < 0.2 mg/L in all wells but one, which had NH₄⁺ at 3 mg/L. Similarly, NH₄⁺ was below the South African National Standard (2 mg/L) in all water samples analyzed by Vinger et al. (2012). Padmasiri et al. (1992) reported that soil concentrations of NH₄⁺ decreased substantially between 1 and 1.5 m from latrine pits. Ammonia tends to accumulate and persist under anaerobic conditions, and high concentrations are likely when the water table intersects the base of the latrine pit (Ahmed et al. 2002; Baars 1957; Dzwairo et al. 2006).

**Other chemicals derived from pit latrines.** Nitrite concentrations in well water from near…
latrines have typically been below drinking water standards (Baars 1957; Vinger et al. 2012), although when present, it has been found in association with nitrate and chloride (Caldwell 1938b; Caldwell and Parr 1937). Phosphate is fairly immobile, and when it was released from latrines, its penetration into soils was minimal (Padmasiri et al. 1992); peat liners further reduced potential transport (Nichols et al. 1983). Accordingly, phosphate concentrations in well water have not been detected at concentrations above water quality standards in association with pit latrines (Zingoni et al. 2005).

Elevated groundwater potassium concentrations may also be derived from latrines, and concentrations have been shown to correlate with those of nitrate and chloride (Banks et al. 2002). The effect of latrines on sulfate concentrations remains unclear, perhaps because of the prevalence of sulfate sources and the number of processes that may remove sulfate from solution in the subsurface. Although Banks et al. (2002) found no evidence that latrines influenced sulfate concentrations in well water, Chidavaenzi et al. (2000) observed increases in sulfate concentrations near latrines during the wet season. Latrines also have been associated with increased well-water turbidity (Dzwairo et al. 2006). Finally, Mafa (2003) measured high concentrations of dissolved organic carbon in wells downstream of latrines, which might contribute to reducing conditions and elevated dissolved iron concentrations (Zingoni et al. 2005).

Discussion

Pit latrine guidelines for mitigating groundwater impacts. In relation to on-site sanitation, the factors controlling transport of microbial and chemical contaminants in the subsurface have been the subject of several reviews (BGS 2002; Dillon 1997; Gerba et al. 1975; Lewis et al. 1982; WHO 2006), and there is extensive literature that more broadly quantifies contaminant transport processes in groundwater (e.g., Schijven and Hassanizadeh 2000). Soil/rock type, natural and human-altered groundwater flow rates and paths, and the biogeochemical environment of the subsurface all govern contaminant travel distances and rates. Tracking the movement of contaminants is further complicated by microbial die-off and chemical transformations, which may occur heterogeneously over space and time. The potential for widespread groundwater contamination from pit latrines is also affected by social factors, such as latrine use, latrine densities, maintenance, and groundwater pumping. Latrine type, design, materials, and construction quality also influence contaminant containment and leaching from pit latrines. Thus, to effectively evaluate the safety of pit latrine and groundwater source proximity, both environmental and anthropogenic factors must be considered.

Among the studies we reviewed, specific recommendations for minimizing latrine effects on groundwater quality varied. Nichols et al. (1983) suggested that pit liners, such as peat liners, should not be used as a substitute for proper soil conditions, and recommended that latrines not be built in thin, rocky soils. Dzwairo et al. (2006) highlighted the need to (a) analyze critical parameters such as depth of the infiltration layer and direction of ground-water flow; (b) develop alternative sanitation options, such as raised or lined pit latrines, to minimize groundwater impacts; and (c) apply an integrated approach, involving geotechnology and hydrogeology, to solve sanitation problems. Pujari et al. (2012) recommended that latrines be discouraged in rocky areas with shallow water tables. They also suggested that systematic lithological and hydrogeological mapping be conducted and that parameters such as the depth of the water table, soil characteristics, and rock strata be considered prior to installing latrines. Pujari et al. (2012) advised that groundwater sources in areas served by on-site sanitation systems should be monitored by responsible agencies; monitoring should include nitrate, chloride, and fecal coliforms. To minimize the leaching of nitrate, Jacks et al. (1999) suggested (a) painting latrine ventilation tubes black to increase daytime ventilation rates; (b) increasing the pH of latrine contents to increase ammonia volatilization; (c) sealing pits to prevent nitrate leaching and promote denitrification; and (d) diverting urine for use as a fertilizer for deep-rooted crops. Finally, a number of the studies suggested that pit latrines did not appear to pose a major threat to groundwater quality or public health (Caldwell 1938a, 1938b; Chidavaenzi et al. 2000; Howard et al. 2003; Kliger 1921); this conclusion, which runs counter to general consensus, may have been influenced by the specific latrine siting, environmental conditions, and experimental designs of the studies.

Given the varying transport distances observed for microbiological and chemical contaminants originating from pit latrines (Figure 2), researchers have identified a range of latrine siting guidelines. In their comprehensive review about the risks for groundwater contamination by on-site sanitation sources, Lewis et al. (1982) noted the “traditional” guideline of 15 m as a safe distance between wells and sanitation units. On the basis of statistical associations between latrines and nitrate concentrations in water sources, Tandia et al. (1999) recommended distances of 20 m, 36 m, and 48 m for pits that are in use for < 1 decade, 1–2 decades, and > 2 decades, respectively. Banks et al. (2002) suggested that pit latrines should be located no less than 15–30 m from groundwater abstraction points and should terminate no less than 1.5–2.0 m above the water table. Banerjee (2011) concluded that, with the exception of fissured rock, the safe distance between a pit latrine and water source is 10 m. Vinger et al. (2012) suggested that wells are likely to be contaminated if pit latrines are < 12 m away.

Countries and development agencies often have siting standards for latrine construction. In Haiti, for example, latrines must be sited at least 30 m from any surface water source or drinking water source, and the bottom of the pit must be at least 1.5 m above the maximum height of the water table (Reed 2010). South Africa’s groundwater guidelines recommend that pit latrines are located at least 75 m from water sources (Still and Nash 2002). The WHO suggests minimal risk of groundwater pollution where > 2 m of relatively fine soil exists between a pit and the groundwater table, assuming fill rates are < 50 L/m²/day (Francyes et al. 1992). Furthermore, 15 m is suggested as the safe lateral separation between pit latrines and the groundwater supply; this distance can be reduced if the well is not directly downhill of the pit (Francyes et al. 1992). However, in a more recent and conservative recommendation that seeks to account for a wide variety of contexts, WaterAid (2011) suggests that latrines and water sources should be at least 50 m apart (WaterAid 2011). For disaster response situations, the Sphere Project (2011) has recommended 30 m as a minimum standard for the lateral distance between on-site sanitation systems and water sources, although this value could be adjusted based on the nature of subsurface features.

Overall, threats to groundwater quality from on-site sanitation can be mitigated through technology design, risk assessment, development of protection zones, and monitoring (Lawrence et al. 2001; Lewis et al. 1982; Robins et al. 2007). For septic systems and more complex on-site sanitation technologies, manuals and siting guidelines are widely accessible (e.g., U.S. Environmental Protection Agency 2002), and technology choices generally depend on the available land area for drain fields and vertical separation to the water table. Step-by-step strategies for site-specific analyses of safe sanitation options appropriate for low-income countries have been outlined by the BGS (Lawrence et al. 2001). The BGS guidelines provide a set of rules for determining the optimum horizontal separation between sanitation facilities and drinking-water sources for a variety of hydrogeological environments. These guidelines have been tested in Bangladesh (Ahmed et al. 2002), Uganda (Howard et al. 2003), and Argentina (Blarasin et al. 2002) and have been advocated as sensible practice for aquifers for which data are limited and therefore do not otherwise lend themselves to conventional
vulnerability assessment (Ahmed et al. 2002; Blarasin et al. 2002; Howard et al. 2003).

Moving forward. Pit latrine and groundwater usage are prevalent in a rapidly growing segment of the world population. Given that approximately 1.11 billion people currently have no sanitation facility [see Supplemental Material (http://dx.doi.org/10.1289/ehp.1206028)], pit latrine coverage is expected to increase as people attempt to move up the sanitation ladder from open defecation to basic sanitation (WHO/UNICEF 2012c). Our analysis of existing literature reveals five key knowledge gaps that could be addressed to improve our understanding and management of groundwater contamination from pit latrines.

Siting latrines in relation to wells. Groundwater flow paths are among the most important factors controlling contaminant transport from latrines to water points. In many areas, the subsurface flow pattern is unknown. Groundwater flow models are needed to better define the limits of chemical transport and pathogen dispersion (Pedley et al. 2006), particularly for complex groundwater systems such as fractured rock aquifers. It is often difficult to determine whether a contamination source is a pit latrine or animal waste and agricultural sources; better assessment of groundwater flow conditions will enable identification of dominant contaminant sources. In locations where horizontal separation of latrines and water points is not possible (e.g., routinely flooded regions), vertical separation has been promoted (Lawrence et al. 2001), but such siting guidelines are not well defined. An improved understanding of contaminants leaching from pit latrines and the transport pathways involved is needed particularly for managing sanitation in densely populated areas, such as refugee camps and informal settlements, as well as areas with rapidly growing populations. Siting guidelines need to consider population pressures and the potential for increased groundwater abstraction, which will alter transport distances and rates.

Understudied and emerging contaminants. To date there has been a focus on a limited number of contaminants that may be found in human excreta. Microbiological monitoring has primarily relied on fecal indicator bacteria, whereas nitrate has been the focus of most chemical studies. In a recent study of groundwater in rural Bangladesh, Ferguson et al. (2012) noted that culture-dependent fecal indicators were not always able to predict total bacterial pathogens. Pit latrine additives are used to reduce pit contents, odor, and insect problems, but little research exists on their makeup or the prevalence of their use (Buckley et al. 2008). Organic chemical contaminants, including endocrine disruptors and pharmaceuticals, that may be excreted in urine and feces and may persist in the environment have not been investigated proximate to pit latrines, but they should be quantified and their potential for transport needs to be assessed. There has also been little research on disposal of other chemicals, such as lime, pesticides, and cleaning agents, into latrines. Finally, it remains unclear whether effects of latrine wastes on the geochemical environment of groundwater may increase downstream contamination. For instance, excreta contains high quantities of organic carbon (Feacham et al. 1983), and plumes of carbon from latrines may promote reducing conditions within groundwater (Mafa 2003), leading to reductive release of trace elements associated with native aquifer materials (Harvey et al. 2002).

Global climate change. Global climate change is widely recognized as a threat to the safety and reliability of drinking water and sanitation supplies, particularly in low-income countries (WHO 2009; World Bank 2012). To date, no studies have specifically addressed these threats in relation to pit latrines and groundwater quality. Many sprawling urban slums, as well as poor rural communities, are currently situated in coastal zones that are flood prone or have high groundwater tables, especially in East Asia (Djonopoputo et al. 2010). Rising sea levels will increase the prevalence of flooding and slowly raise groundwater levels, limiting the ability for safe vertical separation between latrine pits and the saturated zone. Over shorter time periods, escalation of storm intensities will increase the probability that groundwater tables will rise above the bottoms of pits at some point during the year; thus, it is likely that contaminant transport from pit latrines to groundwater will increase. Flooding will also likely undermine efforts to increase access to basic sanitation. Urban planning and housing development programs will need better estimates of the potential effects of climate change on on-site sanitation, as well as additional information to determine appropriate sanitation facility designs for different target populations.

Improved sanitation technologies. Technological upgrades to pit latrines may substantially reduce microbiological and chemical threats to groundwater quality. Latrine liners can minimize seepage of pit contents to groundwater, and raised latrines may help minimize groundwater contamination by increasing vertical separation and promoting aerobic digestion of waste (Dillon 1997; Drwairo et al. 2006; Nichols et al. 1983). Urine-diverting toilets, painted ventilation tubes, and chemical amendments to latrines can minimize nitrate formation and release to groundwater (Jacobs et al. 1999). Composting toilets and ecological sanitation technologies may reduce microbial risks and minimize chemical leaching from pit latrines (Dillon 1997; Endale et al. 2012). However, it remains unclear whether these alternative systems are affordable and culturally acceptable to poor populations in low-income countries (Mariwah and Drangert 2011).

Balancing risks. Despite the potential for groundwater contamination, pit latrines remain an important strategy for improving human excreta disposal. These systems are the most basic option for low-income countries to decrease rates of open defecation and increase access to improved sanitation. An intensive effort is needed to develop more robust—and yet viable—approaches to siting pit latrines and water sources. Proposed guidelines should be tested empirically to ensure protection of groundwater quality after implementation under local conditions.

Conclusions

We estimate that approximately 1.77 billion people around the world use pit latrines. This number is expected to increase as populations grow and countries strive to meet the Millennium Development Goals. The use of groundwater as a primary drinking-water source is also increasing. Accordingly, there is a growing need to understand how pit latrines may adversely impact groundwater quality and human health.

Despite the widespread global reliance on both pit latrines and groundwater, we found a limited number of studies that have explicitly examined links between groundwater pollution and contamination from pit latrines. Within these studies, the quality of experimental techniques and chosen indicator contaminants varied greatly. In multiple studies conducted near the same location, there were substantial differences in transport distances of microbiological and chemical contaminants (Caldwell 1937a, 1937b, 1938a, 1938b; Caldwell and Parr 1937). Nevertheless, based on available reports, researchers who looked for groundwater contamination from pit latrines frequently detected it, and studies observed travel distances of up to 25 m, 50 m, and 26 m for unsafe concentrations of bacteria, viruses, and chemicals, respectively (Caldwell 1937b; Caldwell and Parr 1937; Verheyen et al. 2009). Although these contaminant transport distances could potentially be exceeded under certain conditions (e.g., in fractured rock aquifers), most studies of pit latrine-derived contaminants actually showed transport distances that were less than half of the maximum values. Areas with shallow groundwater and areas prone to flooding present the greatest risks, because vertical separation is required between the base of latrine pits and the saturated zone.

The ability to make informed decisions about water and sanitation options is largely inhibited by a scarcity of data, especially regarding the influence of environmental conditions on potential contamination. Guidelines
are available for site-specific assessment, and general procedures for siting latrines with respect to water points are common (Lawrence et al. 2001). However, recommendations for mitigating groundwater impacts can be both qualitatively and quantitatively variable, and it remains unclear whether these guidelines can be implemented under local conditions. Many countries already face serious developmental challenges and may not have the resources—human and economic—to implement guidelines (Robins et al. 2007).

In general, guideline sites vary greatly, and it is often unknown which (if any) empirical studies were used to derive the guidelines. Thus, there is a need to empirically test the effectiveness of specific guidelines under a variety of conditions in order to better merge pit latrine siting guidelines with realistic groundwater threats. Given the scale of pit latrine use, future studies must examine additional contaminants beyond standard indicators, monitor temporal changes in water quality parameters, and evaluate alternative technologies. In addition, guidelines are needed to better understand the effects of population pressures and climate change in order to make more informed decisions that optimize latrine and groundwater use and improve environmental and human health.

REFERENCES

Ahmed KM, Khandkar ZZ, Lawrence AR, Macdonald DMJ, Islam MS. 2002. Appendix A: an investigation of the impact of on-site sanitation on the quality of groundwater supplies in two peri-urban areas of Dhaka, Bangladesh. In: Assessing Risk to Groundwater from On-site Sanitation: Scientific Review and Case Studies. Keyworth, UK: British Geological Survey, 37–57. Available: http://i4.dfid.gov.uk/pdfynomials/r6822.pdf [accessed 26 March 2013].

Albonico M, Allen H, Chitsulo L, Engels D, Gabrielli AF, Savoli L. 2008. Controlling soil-transmitted helminthiasis in pre-school-age children through preventive chemotherapy. PLoS Negl Trop Dis 2(6): e120. doi:10.1371/journal.pntd.0000126 [Online 26 March 2008].

Baars JK. 1957. Travel of pollution, and purification en route, in sandy soils. Bull World Health Organ 16:727–747.

Banerjee G. 2011. Underground pollution travel from leach pits of on-site sanitation facilities: a case study. Clean Technol Environ Policy 13(3):489–497.

Banks D, Karnachuk OV, Parnachev VP, Holden W, Frengstad B. 2008. Assessing Risk to Groundwater from On-site Sanitation: Scientific Review and Case Studies. Keyworth, UK: British Geological Survey, Available: http://i4.dfid.gov.uk/pdfynomials/r6822.pdf [accessed 26 March 2013].

Blasini M, Cabrera A, Frigerio C, Bettner S. 2002. Appendix C: Risk of groundwater pollution by on-site sanitation, geomorphological models and geoindicators. Rio Guato City, Argentina. In: Assessing Risk to Groundwater from On-site Sanitation: Scientific Review and Case Studies. Keyworth, UK: British Geological Survey, 94–105. Available: http://i4.dfid.gov.uk/pdfynomials/r6822.pdf [accessed 26 March 2013].

Buckley CA, Foxon KM, Brouckaert CJ, Rodda N, Nwanevi C, Balboni E et al. 2008. Scientific support for the Design and Operation of Ventilated Improved Pit Latrines (VIPs) and the Efficiency of Improved Ventilation Systems. WRC Report No. T. 37050. Pretoria: Gezina, South Africa: Water Research Commission. Available: http://www.wrc.org.zaknowledge/52042%20documents/ Research%20Reports/T1557-98%20Developing%20communities.pdf [accessed 26 March 2013].
Maputaland. In: Water Institute of Southern Africa Biennial Conference. Durban, South Africa: Water Institute of Southern Africa, 1–6. Available: http://www.sswm.info/sites/default/files/reference_attachments/STILL%20and%20NAS%202002%20Groundwater%20contamination%20due%20to%20pit%20latrines%20located%20in%20sandy%20aquifer.pdf [accessed 29 March 2013].

Tandia AA, Diop ES, Gaye CB. 1999. Nitrate groundwater pollution in suburban areas: example of groundwater from Yeumbeul, Senegal. J Afr Earth Sci 29(4):809–822.

UN (United Nations). 2008. The Millennium Development Goals Report 2008. New York: UN. Available: http://www.un.org/millenniumgoals/pdf/The%20Millennium%20Development%20Goals%20Report%202008.pdf [accessed 27 March 2013].

UN (United Nations). 2011. World Population Prospects: The 2010 Revision, CD-ROM Edition. Data download available: http://esa.un.org/unpd/wpp/Excel-Data/population.htm [accessed 1 April 2013].

UNICEF. 2012. Multiple Indicator Cluster Surveys. Available Reports/Datasets. Available: http://www.childinfo.org/mics_available.html [accessed 25 October 2012].

USAID. 2012. Measure DHS. Available Datasets. Available: http://www.measuredhs.com/data/available-datasets.cfm [accessed 25 October 2012].

U.S. Environmental Protection Agency. 2002. Onsite Wastewater Treatment Systems Manual. EPA/625/R-00/008. Washington DC: U.S. Environmental Protection Agency. Available: http://water.epa.gov/type/groundwater/uc1/class5/upload/2007_12_12_12_class5_techguide_12_class5_2002_onsite_wwt.Sys_man.pdf [accessed 26 March 2013].

van Ryneveld MB, Fourie AB. 1997. A strategy for evaluating the environmental impact of on-site sanitation systems. Water SA 23(4):279–291.

Verheyen J, Timmen-Wego M, Laudien R, Boussaad I, Sen S, Koc A, et al. 2009. Detection of adenoviruses and rotaviruses in drinking water sources used in rural areas of Benin, West Africa. Appl Environ Microbiol 75(9):2798–2801.

Vinger B, Hlophe M, Selvaratnam M. 2012. Relationship between nitrogenous pollution of borehole waters and distances separating them from pit latrines and fertilized fields. Life Sci J 9(1):402–407.

Wade TJ, Pai N, Eisenberg JNS, Colford JM Jr. 2003. Do U.S. Environmental Protection Agency water quality guidelines for recreational waters prevent gastrointestinal illness? A systematic review and meta-analysis. Environ Health Perspect 111:1102–1109.

WaterAid. 2011. Technology Notes. Available: http://www.wateraid.org/documents/plugin_documents/technology_notes_2011.pdf [accessed 5 December 2012].

WHO (World Health Organization). 2006. Protecting Groundwater for Health: Managing the Quality of Drinking-water Sources. Geneva: WHO. Available: http://www.who.int/water_sanitation_health/publications/protecting_groundwater/en/ [accessed 26 March 2013].

WHO (World Health Organization). 2009. Protecting Health from Climate Change: Connecting Science, Policy and People. Geneva: WHO. Available: http://whqlibdoc.who.int/publications/2009/9789241598880_eng.pdf [accessed 29 March 2013].

WHO (World Health Organization). 2011. Guidelines for Drinking-water Quality. 4th ed. Geneva: WHO. Available: http://whqlibdoc.who.int/publications/2011/9789241546151_eng.pdf [accessed 1 April 2013].

WHO (World Health Organization)/UNICEF. 2010. Progress on Sanitation and Drinking-water–2010 Update. Available: http://whqlibdoc.who.int/publications/2010/9789241563956_eng_full_text.pdf [accessed 5 December 2012].

WHO (World Health Organization)/UNICEF. 2012a. Estimates for the Use of Improved Sanitation Facilities: China. Available: http://www.wssinfo.org/fileadmin/user_upload/resources/CHN_san.pdf [accessed 1 April 2013].

WHO (World Health Organization)/UNICEF. 2012b. Estimates for the Use of Improved Drinking-Water Sources: China. Available: http://www.wssinfo.org/fileadmin/user_upload/resources/CHN_wat.pdf [accessed 1 April 2013].

WHO (World Health Organization)/UNICEF. 2012c. Progress on Drinking Water and Sanitation: 2012 Update. Available: http://www.unicef.org/media/files/JMPreport2012.pdf [accessed 5 December 2012].

World Bank. 2012. Turn Down the Heat: Why a 4°C Warmer World Must Be Avoided. Washington, DC: The World Bank. Available: http://climatechange.worldbank.org/sites/default/files/Turn_Down_the_Heat_Why_a_4_degree_centigrade_warmer_world_must_be_avoided.pdf [accessed 27 March 2013].

World Bank. 2013. How We Classify Countries. Available: http://data.worldbank.org/about/country-classifications [accessed 3 April 2013].

Zingoni E, Love D, Magadza C, Macey W, Musiwa K. 2005. Effects of a semi-formal urban settlement on groundwater quality Epworth (Zimbabwe): case study and groundwater quality zoning. Phys Chem Earth 30(11–16):680–688.