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Water and Sanitation in Developing Countries : Geochemical Aspects of Quality and Treatment

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Safe drinking water and basic sanitation are key elements of the Millennium Development Goals, a United Nations initiative. The microbial quality of drinking water is inherently linked to sanitation practices because fecal pathogens are the most common source of drinking-water contamination in developing countries. Filtration of water through soil and aquifer sediments can provide natural protection against pathogens, and this makes groundwater an attractive option for safe drinking-water supply. Groundwater quality may, however, be compromised by the leaching of natural chemical constituents from geologic materials. Conversely, geochemical processes provide the basis both for the removal of such contaminants and for the recovery of nutrients from wastewater through physicochemical treatment.

SAFE DRINKING WATER: THE LINK TO SANITATION

Although diarrhea has become a rare and mainly inconvenient condition in developed countries, it remains a leading killer, especially of children, in other parts of the world. Each year 1.8 million children die before their fifth birthday because of diarrhea, nearly all in developing countries. Diarrhea kills more people than AIDS, tuberculosis, or malaria; it kills more children than all three combined. It is estimated that 88% of these deaths could be prevented by safe water supply, sanitation, and hygiene (Montgomery and Elimelech 2007; WHO 2008; Hunter et al. 2010).

The presence in drinking water of pathogens that cause diarrhea, cholera, and other diseases is nearly always caused by fecal contamination. Globally, 2.6 billion people use primitive sanitation (FIG. 1); open defecation is practiced by 1.1 billion people—more than 1 person in 5 in developing regions. Nearly 900 million people collect drinking water from vulnerable sources, such as rivers, ponds, and shallow open wells (FIG. 1). Almost half of the population of the world faces water scarcity, and problems of water quality and quantity are increasing (WHO/UNICEF 2010).

[insert Figure 1 (upper and lower panels) here]

Figure 1. Worldwide use of improved sanitation (upper panel) and drinking-water sources (lower panel) in 2008. See the text for a definition of improved sanitation and drinking-water sources. Source: WHO/UNICEF 2010. Used with permission from WHO.

Although this situation seems dire, access to improved water sources (defined as those that are protected, by construction or intervention, from external contamination, particularly from fecal matter) and improved sanitation (defined by the hygienic separation of human excreta from human contact) has been steadily increasing (WHO/UNICEF 2010). Such improvements have been shown to decrease diarrheal disease significantly (Fewtrell et al. 2005). At the United Nations Millennium Summit in 2000, 187 countries made a commitment to achieve eight Millennium Development Goals (MDGs), including the target "*to halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation.*" Success in achieving this target is judged by the proportion of the population using an improved drinking water source and/or an improved sanitation facility. The world is on track to meet the target of 89% access to improved water sources: 1.8 billion people have gained access to improved sources since 1990. Progress in sanitation is slower. Even though 1.3 billion people have gained access since 1990, there is little chance of meeting the global sanitation target of 77% coverage by 2015 (WHO/UNICEF 2010).

Basic sanitation is particularly important because of the high pathogen loads that can be associated with feces (Feachem et al. 1983). Improper disposal of fecal matter results in the contamination of water resources, especially surface water. Throughout most of the world, ponds, lakes, and rivers have high fecal loads, and this causes diseases among people who must rely on these sources for their drinking water. Water collected from "improved sources" is not necessarily safe; moderate to heavy fecal contamination has been reported in dug wells, boreholes, and piped water systems (Moe et al. 1991; Godfrey et al. 2006). Even when water quality is good at the source, contamination before consumption can occur due to collection and transport in unclean storage containers and to contact with unclean hands and utensils (Wright et al. 2004). Good hygiene practices are thus a critical component of disease prevention.

Despite the human health hazards associated with feces, human excreta can also provide benefits. “Ecological sanitation” aims to recover nutrients, energy, and/or water for use in agriculture while preventing the spread of pathogens (Schönning and Stenström 2004).

CLOSING THE NUTRIENT CYCLE: PHOSPHORUS RECOVERY FROM HUMAN WASTE

Eutrophication (oversupply of nutrients resulting in excessive phytoplankton growth) and hypoxia (low dissolved oxygen concentration) in inland and coastal waters are a result of excess loading of phosphorus associated with inadequate sewage treatment (Manning 2008). In addition, the phosphate in most commercial fertilizers is currently derived from mined, nonrenewable resources. Production of phosphate from these sources is expected to decline after 2030 (Cordell et al. 2009b), giving rise to a “peak phosphorus” phenomenon analogous to “peak oil.” The possible consequences of this were foreshadowed in 2007–2008 when the price of fertilizer rose over 700% during a 14-month period. This provides a powerful incentive to recover phosphorus from crop residues, animal manure, and human excreta. A potential added benefit would be a reduction in harmful by-products of phosphate production, including radioactive phosphogypsum (Cordell et al. 2009a).

Urine is particularly rich in nutrients, as it contains high levels of phosphorus (740 mg/L), nitrogen (7700 mg/L), potassium (2200 mg/L), and sulfate (1500 mg/L) (Udert et al. 2003). The mineral struvite, $(NH_4)MgPO_4 \cdot 6H_2O$, has been recovered from wastewater in treatment plants in Japan and North America for some time (Parsons and Smith 2008). Arid and semiarid regions in developing countries, however, lack both the infrastructure and the water needed to operate such systems. Under these conditions, the precipitation of struvite from urine collected in urine-diverting toilets could produce fertilizer as a valuable product that would promote both food security and sanitation (Tilley et al. 2009b). Treatment can be performed at various scales (FIG. 2). Nutrients are recovered in a compact form that can be exported efficiently to agricultural areas. The concept of recovering value from excreta is not new, but current resource scarcity and economic incentives have made the concept worth revisiting, especially as a tool to help eradicate extreme poverty and hunger.

[Figure 2 here]

Figure 2. Pilot-scale installation in Nepal for the recovery of struvite from urine. Struvite was precipitated by the addition of bittern, a waste product from salt manufacturing, as a source of magnesium. After 10 minutes of mixing and 24 hours of settling, struvite was collected on a screen at the bottom of the reactor. Source: (Tilley et al. 2009a). Used by permission from Eawag.

DRINKING WATER SUPPLY: THE RELATIVE ADVANTAGES OF SURFACE WATER AND GROUNDWATER

Drinking water supplies are provided by both surface water and groundwater, though in widely varying proportions. Globally, each source provides about 50% of drinking-water needs, but in many countries groundwater is the principal drinking-water source: approximately 70% in the European Community and nearly 100% in many developing regions (UNESCO/IHP 2004). In the United States, two-thirds of piped water (more in large cities) comes from surface water, but in rural areas, drinking water is frequently not obtained from public water suppliers and nearly all domestic self-supply is from groundwater (Kenny et al. 2009).

Groundwater in rural settings is generally assumed to be protected from pathogens by natural filtration. This natural protection can, of course, be compromised by inadequate well completion or wellhead protection; inadequate filtration in, for example, karstic aquifer systems can also affect this protection (Macler and Merkle 2000). Despite these caveats, the benefit of protection from pathogens has been a major motivation in shifting drinking-water sources from surface water to groundwater in developing countries.

The reliable availability of drinking water also varies geographically and seasonally and can be quite different for surface water and groundwater. Water table elevations can undergo substantial seasonal variations, and excessive pumping can draw the water table down below the level of shallow wells. Nonetheless, the availability of groundwater is often more reliable than that of surface water. Ephemeral streams are common in arid and semiarid areas, and surface waters can be diverted for irrigation or hydropower generation at the expense of downstream (and often transboundary) water supply.

The degradation of water resources is often obvious, even to casual visual inspection, in the case of surface waters. The degradation of groundwater resources is usually less apparent, making the assessment of actual or potential contamination a critically important activity (Zaporozec 2002). Groundwater contamination is often difficult or even impossible to reverse. Thus efforts must be made to protect groundwater from contamination related to, for example, the agricultural use of fertilizers and pesticides, mining and industrial activities, and improper disposal of solid waste and domestic wastewater.

Even in the absence of anthropogenic contamination, however, the quality of groundwater can be inadequate for its use as drinking water. Many groundwaters are brackish or saline. In such cases, taste alone precludes its use as drinking water without treatment. Naturally occurring substances in groundwater can, however, have serious adverse health impacts without any detectable taste or odor. These are generally inorganic substances derived from geologic materials and are referred to as geogenic contaminants. The two most important geogenic contaminants are arsenic (Ravenscroft et al. 2009) and fluoride (Fawell et al. 2006). Hundreds of millions of individuals are exposed to these geogenic contaminants at levels 10- to 100-fold in excess of drinking-water standards. This exposure is associated with severe chronic health effects, including cancer (Hopenhayn 2006).

Geogenic Contaminants

The occurrence of geogenic contaminants in groundwater is related not only to the local and regional geology but also to the conditions that facilitate contaminant release from aquifer sediments. For example, elevated arsenic concentrations in groundwater are often associated with moderately reducing (i.e. iron-reducing) conditions, but arsenic can also be mobilized under oxidizing conditions at sufficiently high alkalinity (i.e. high-pH conditions) (Smedley and Kinniburgh 2002). Alterations in hydrologic conditions, specifically in recharge and extraction patterns, have also been implicated in the mobilization of arsenic (Neumann et al. 2010; Winkel et al. 2011).

Recent efforts at regional- and global-scale mapping have been successful in identifying parameters that can serve as reliable proxies for settings and conditions that favor mobilization of geogenic contaminants (Amini et al. 2008). In Sumatra, Southeast Asia, predictions of arsenic occurrence at concentrations above 10 μg/L based on regional geology and soil properties were verified by observations made in previously untested areas (Fig. 3) (Winkel et al. 2008).

[Figure 3 here]

Figure 3. Map of Sumatra (**A**) and, for southern Sumatra, a map (**B**) showing areas where the risk of As occurrence at concentrations > 10 μg/L is high (probability > 0.4) or low (probability < 0.4) and measured As concentrations. These predictions and data can be compared with a geologic map (C). Source: (Winkel et al. 2008). Used by permission from the Nature Publishing Group.

The massive human exposure to arsenic in South and Southeast Asia highlights both the importance of geogenic contaminants and the need to exercise caution in exploiting new groundwater resources. Mapping and predictions can be useful tools in raising the awareness of potential threats but are obviously not substitutes for water-quality testing. The use of groundwater containing elevated concentrations of geogenic contaminants may, in some cases, be avoided by using other drinking-water sources. Alternatively, appropriate water-treatment technologies may be used to produce drinking water that meets water-quality standards.

APPROPRIATE WATER-TREATMENT TECHNOLOGIES

In industrialized countries, surface water is routinely treated before distribution to the public, but the extent of groundwater treatment varies substantially. Limits to the natural protection afforded by groundwater supplies are reflected in the U.S. Ground Water Rule (GWR) (USEPA 2006). The GWR requires identification of groundwater sources that are vulnerable to fecal contamination and specifies corrective action for contaminated groundwater sources, which may include treatment (i.e. disinfection).

In developing countries, however, establishing effective drinking-water treatment poses considerable challenges. In this context, the substitution of an alternative source of water is often viewed as a preferable option to treatment. As already mentioned, this strategy has been pursued in the massive shift from surface water to groundwater in many developing countries. More recently, a shift from shallow to deep wells has been both recommended and implemented as a measure to reduce exposure to arsenic-contaminated groundwater in Bangladesh (Ahmed et al. 2006).

A central issue in selecting treatment technologies in developing countries is that the infrastructure for water distribution is often inadequate or even nonexistent. This precludes the centralized model for water treatment that is most common in the urban and suburban areas of industrialized countries. The lack of water-distribution infrastructure has led to an emphasis on decentralized water treatment, even at the household level (Sobsey et al. 2008).

The household treatment of drinking water in developing countries for aesthetic purposes (e.g. turbidity removal) is not uncommon. In such cases, individuals are self-motivated to perform the treatment, and the lack of consistent performance has little consequence beyond aesthetics. The issue of consistent and effective treatment is both more consequential and more problematic when the intended outcome is a health benefit rather than an aesthetic improvement. For example, solar disinfection (SODIS) is a widely-practiced method of household water treatment in which transparent (usually plastic) bottles are filled with low-turbidity water and exposed to sunlight for six or more hours (www.sodis.ch). Despite the proven efficacy of pathogen inactivation by SODIS, the rates of both initial uptake and lapse from practice have been shown to be strongly influenced by the promotion methods. Consistent practice cannot be assumed but must be both continuously encouraged and carefully monitored (Moser and Mosler 2008).

Treatment Technologies for Geogenic Contaminants

In the case of geogenic contaminants, Vietnam provides a useful example in which a traditional practice adopted for its aesthetic benefits could also be effective in addressing the health risks posed by elevated arsenic concentrations in local groundwater. Rural households in Vietnam traditionally use sand filters to remove iron from groundwater because of its undesirable taste. An added benefit is efficient arsenic removal (average 80%) via the oxidation and adsorption of arsenic to iron phases that precipitate during filtration (FIG. 4). This process requires a sufficiently high iron concentration, is less effective in the presence of high levels of phosphate, and may not meet stringent drinking-water standards in all cases. Nonetheless, sand filters have become a socially established technology with a proven record of decreasing arsenic exposure (Berg et al. 2006).

[Figure 4 here]

Figure 4. Comparison of treatments for the removal of arsenic (left) and fluoride (right). Arsenic is removed by sorption onto iron(III) oxyhydroxides formed by the oxidative precipitation of iron(II) that occurs naturally in reducing groundwater. Fluoride is removed by filtration through hydroxyapatite through a combination of ion exchange and precipitation processes.

The challenges associated with establishing new practices for the removal of geogenic contaminants at the household level can be illustrated by the case of fluoride removal in Ethiopia. The problem of fluoride contamination in the Rift Valley is well known (Tekle-Haimanot et al. 2006). The deep and shallow wells used as drinking-water sources in this region commonly have fluoride concentrations well above the World Health Organization (WHO) guideline value of 1.5 mg/L. This value is exceeded in over 41% of drinking-water sources, and fluoride concentrations can be as high as 20 mg/L. Intake of moderate levels of fluoride causes dental discoloration and pitting, which affects 80% of children in the Ethopian Rift Valley (Tekle-Haimanot et al. 2006). Higher exposures lead to crippling skeletal fluorosis, which is characterized by extreme bone deformation.

The mitigation of fluoride-contaminated groundwater used for drinking has recently become a priority issue for the Ethiopian government. Bone char has been identified as an inexpensive fluoride-removal filter medium, though saturation is commonly reached within a few months (FIG. 4). Filter life can be prolonged by the addition of soluble calcium phosphate salts, which promote the precipitation of hydroxyapatite and/or fluorapatite on the surface of the bone char (Jacobsen and Dahi 1997). This technology is acceptable to the local population but is not yet widely implemented. Among the issues that remain to be solved are the roles of government, the private sector, and nongovernmental organizations in the provision, monitoring, maintenance, and replacement of filters and filter media.

In general, issues that arise with household treatment include the reliability of performance, adequate maintenance and replacement of components, willingness and ability of households to pay for consumables, and appropriate disposal of residuals (e.g. spent filter material or solids collected from filter cleaning). Issues of operation and maintenance can be particularly challenging when there is no obvious signal of deteriorating performance (or even failure). Some of these issues may be more easily addressed at the community rather than the household level. Operation at the community level can achieve some economies of scale and can support some level of professionalization for operation and maintenance. One trade-off, however, is that shifting treatment away from the household means that the treated water must be transported from the site of treatment to the household; this burden traditionally falls to women and girls (Fig. 5). This investment of time (and the associated cost to the household) as well as other social factors that may influence patterns in water consumption have been found to be critical determinants of the use of deep wells in Bangladesh (Mosler et al. 2010). Although no treatment is involved in the use of deep wells, there is a decrease in convenience as compared with shallow wells located in an extended family compound.

Figure 5 (optional) here	**Figure 5**. Girls transport water treated for fluoride removal from a central facility to their homes. Used by permission from Eawag.

ROLE OF THE PRIVATE SECTOR

Providing safe drinking water and basic sanitation is a complex task, which is complicated further by differences between dispersed rural communities and densely populated urban areas. Private water suppliers (vendors, tanker truck, and bottled water) provide up to about 30% of the drinking water consumed in urban areas in Latin America (Gleick et al. 2002). Particularly in the late 1990s, large multinational companies began to enter the business of providing water and wastewater services at the municipal level in developing countries. This activity has been fraught with difficulties and has, in many cases, failed to realize the improvements in service and efficiency that were hoped for by the participating public authorities (Prasad 2007). This has led to a reevaluation of the potential for water-supply privatization, but it must be recognized that private-sector participation encompasses a number of different models that must be evaluated in specific contexts (WB 2006). It is important to note that the definition of "improved sources" currently excludes some provision by private water suppliers (e.g. tanker trucks) (WHO/UNICEF 2010). Ideally, the definition of improved water sources would be based on water quality, but monitoring water quality in developing countries poses major challenges.

Privatization in sanitation also plays a complex role in the service chain. Many households rely on private entrepreneurs to empty and transport the wastes from household pits and septic tanks. Although these entrepreneurs represent an important sector of the economy, they are commonly illegal, marginalized, and ostracized (Eales 2005). By failing to recognize the role of private entrepreneurs in sanitation, authorities waive their rights to control the subsequent disposal of collected sludge, a situation that endangers the health of the community. In dense urban slums where space does not permit household facilities, public toilets operated by NGOs or small businesses are common. Although not hugely profitable, they meet a serious need, provide local salaries, and may generate enough income to support spin-off activities. The recovery of water, nutrient and energy from waste at both the large and small scale have already proved lucrative for some entrepreneurs and are likely to become more attractive with increasing energy and fertilizer costs.

OUTLOOK

Providing safe drinking water and basic sanitation in developing countries is a complex task that demands engagement from many sectors. The MDGs are useful in that they give governments concrete targets to meet for both water and sanitation. The MDGs are, however, limited as they are based on pragmatic, operational definitions that, while amenable to monitoring, correspond only indirectly to the desired health outcomes. In addition, even if the targets are met, hundreds of millions of people will still lack access to safe drinking water and quality sanitation. The expertise that geochemists can bring to this issue includes predicting the quality of groundwater and surface waters, explaining the factors and processes that influence water quality, and assisting in the design and optimization of processes for water treatment and the recovery of nutrients from wastewater. Obviously this is only part of the solution, and providing safe water supply and adequate sanitation over the long term will also require that broader issues, such as community demand, local financing and cost recovery, and the operation and maintenance of technical systems, are addressed (Montgomery et al. 2009). Through collaboration with others, however, geochemists could make a valuable contribution to improving human welfare in this arena.

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REFERENCES

Ahmed MF, Ahuja S, Alauddin M, Hug SJ, Lloyd JR, Pfaff A, Pichler T, Saltikov C, Stute M, van Geen A (2006) Ensuring safe drinking water in Bangladesh. Science 314: 1687-1688

Amini M, Abbaspour KC, Berg M, Winkel L, Hug SJ, Hoehn E, Yang H, Johnson CA (2008) Statistical modeling of global geogenic arsenic contamination in groundwater. Environmental Science & Technology 42: 3669-3675

Berg M, Luzi S, Trang PTK, Viet PH, Giger W, Stüben D (2006) Arsenic removal from groundwater by household sand filters: Comparative field study, model calculations, and health benefits. Environmental Science & Technology 40: 5567-5573

Cordell D, Drangert JO, White S (2009a) Preferred future phosphorus scenarios: a framework for meeting long-term phosphorus needs for global food demand. In: Mavinic D, Ashley K, Koch F (eds) International Conference on Nutrient Recovery from Wastewater Streams, IWA Publishing, Vancouver, British Columbia

Cordell D, Drangert JO, White S (2009b) The story of phosphorus: Global food security and food for thought. Global Environmental Change – Human and Policy Dimensions 19: 292-305

Eales K (2005) Bringing pit emptying out of the darkness: a comparison of approaches in Durban, South Africa, and Kibera, Kenya. BPD Sanitation Partnerships Series, www.bpdwaterandsanitation.org/bpd/web/d/doc_131.pdf?statsHandlerDone=1.

Fawell J, Bailey K, Chilton J, Dahi E, Fewtrell L, and Magara Y, (eds) (2006) Fluoride in Drinking-water. WHO Drinking-water Quality Series, IWA Publishing, London, 134 pp. www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf

Feachem RG, Bradley DJ, Garelick H, Mara DD (1983) Sanitation and disease: health aspects of excreta and wastewater management. In: World Bank studies in water supply and sanitation 3. John Wiley & Sons, Washington

Fewtrell L, Kaufmann RB, Kay D, Enanoria W, Haller L, Colford JM (2005) Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. Lancet Infectious Diseases 5: 42-52

Gleick PH, Wolff G, Chalecki EL, Reyes R (2002) The New Economy of Water: The Risks and Benefits of Globalization and Privatization of Fresh Water. Pacific Institute, /www.pacinst.org/reports/new_economy_of_water/new_economy_of_water.pdf.

Godfrey S, Timo F, Smith M (2006) Microbiological risk assessment and management of shallow groundwater sources in Lichinga, Mozambique. Water and Environment Journal 20: 194-202

Hopenhayn, C (2006) Arsenic in drinking water: Impact on human health. Elements 2(2): 103-107.

Hunter PR, MacDonald AM, Carter RC (2010) Water Supply and Health. PLOS Medicine 7(11): e1000361

Jacobsen P, Dahi E (1997) Effect of calcium addition on the defluoridation capacity of bone char. In: 2nd International Workshop on Fluorosis and Defluoridation of Water, Nazret, Ethiopia

Kenny JF, Barber NL, Hutson SS, Linsey KS, Lovelace JK, Maupin MA (2009) Estimated Use of Water in the United States in 2005. United States Geological Survey, Reston, VA, 52 pp, http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf.

Macler BA, Merkle JC (2000) Current knowledge on groundwater microbial pathogens and their control. Hydrogeology Journal 8: 29-40

Manning DAC (2008) Phosphate minerals, environmental pollution and sustainable agriculture. Elements 4: 105-108

Moe CL, Sobsey MD, Samsa GP, Mesolo V (1991) Bacterial indicators of risk of diarrhoeal disease from drinking-water in the Philippines. Bulletin of the World Health Organization 69: 305-317
Montgomery MA, Elimelech M (2007) Water and sanitation in developing countries: Including health in the equation. Environmental Science & Technology 41: 17-24
Montgomery MA, Bartram J, Elimelech M (2009) Increasingfunctional sustainability of water and sanitation supplies in rural Sub-Saharan Africa. Environmental Engineering Science 26: 1017-1023
Moser S, Mosler HJ (2008) Differences in influence patterns between groups predicting the adoption of a solar disinfection technology for drinking water in Bolivia. Social Science & Medicine 67: 497-504
Mosler H-J, Blöchliger OR, Inauen J (2010) Personal, social, and situational factors influencing the consumption of drinking water from arsenic-safe deep tubewells in Bangladesh. Journal of Environmental Management 91: 1316-1323
Neumann RB, Ashfaque KN, Badruzzaman ABM, Ali MA, Shoemaker JK, Harvey CF (2010) Anthropogenic influences on groundwater arsenic concentrations in Bangladesh. Nature Geoscience 3: 46-52
Parsons SA, Smith JA (2008) Phosphorus removal and recovery from municipal wastewaters. Elements 4: 109-112
Prasad N (2007) Social Policies and Water Sector Reform. United Nations Research Institute for Social Development, Geneva, http://ssrn.com/abstract=1025445
Ravenscroft P, Brammer H, Richards K (2009) Arsenic Pollution: A Global Synthesis. Wiley-Blackwell, Chichester, 588 pp
Schönning C, Stenström TA (2004) Guidelines for the safe use of urine and faeces in ecological sanitation systems. EcoSanRes, Stockholm Environmental Institute, Stockholm, 38 pp, www.ecosanres.org/pdf_files/ESR_Publications_2004/ESR1web.pdf
Smedley PL, Kinniburgh DG (2002) A review of the source, behaviour and distribution of arsenic in natural waters. Applied Geochemistry 17: 517-568
Sobsey MD, Stauber CE, Casanova LM, Brown JM, Elliott MA (2008) Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. Environmental Science & Technology 42: 4261-4267
Tekle-Haimanot R, Melaku Z, Kloos H, Reimann C, Fantaye W, Zerihun L, Bjorvatn K (2006) The geographic distribution of fluoride in surface and groundwater in Ethiopia with an emphasis on the Rift Valley. Science of the Total Environment 367: 182-190
Tilley E, Etter B, Gantenbein B, Khadka R, Udert KM (2009a) Struvite from urine in Nepal (STUN). Sandec News 10: 4-5
Tilley E, Gantenbein B, Khadka R, Zurbrügg C, Udert KM (2009b) Social and economic feasibility of struvite recovery from urine at the community level in Nepal. In: Mavinic D, Ashley K, Koch F (eds) International Conference on Nutrient Recovery from Wastewater Streams. IWA Publishing, Vancouver, British Columbia
Udert KM, Larsen TA, Biebow M, Gujer W (2003) Urea hydrolysis and precipitation dynamics in a urine-collecting system. Water Research 37: 2571-2582
UNESCO/IHP (2004) Groundwater resources of the world and their use. http://unesdoc.unesco.org/images/0013/001344/134433e.pdf
US EPA (2006) Ground Water Rule; Final Rule. In, vol 40 CFR Parts 9, 141 and 142
WB (2006) Approaches to Private Participation in Water Services: A Toolkit. The World Bank, http://rru.worldbank.org/Documents/Toolkits/Water/Water_Full.pdf
WHO (2008) The global burden of disease: 2004 update. World Health Organization, Geneva, 146 pp, www.who.int/healthinfo/global_burden_disease/2004_report_update/en/index.html

WHO/UNICEF (2010) Progress on Sanitation and Drinking-water: 2010 Update. WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, 60 pp, www.who.int/water_sanitation_health/publications/9789241563956/en/index.html

Winkel L, Berg M, Amini M, Hug SJ, Johnson CA (2008) Predicting groundwater arsenic contamination in Southeast Asia from surface parameters. Nature Geoscience 1: 536-542

Winkel LHE, Trang PTK, Lan VM, Stengel C, Amini M, Ha NT, Viet PH, Berg M (2011) Arsenic pollution of groundwater in Vietnam exacerbated by deep aquifer exploitation for more than a century. Proceedings of the National Academy of Sciences 108: 1246-1251

Wright J, Gundry S, Conroy R (2004) Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. Tropical Medicine & International Health 9: 106-117

Zaporozec A (2002) Groundwater Contamination Inventory: A Methodological Guide. In: IHP-VI, Series on Groundwater, volume 2, UNESCO, Geneva

Figure 1:

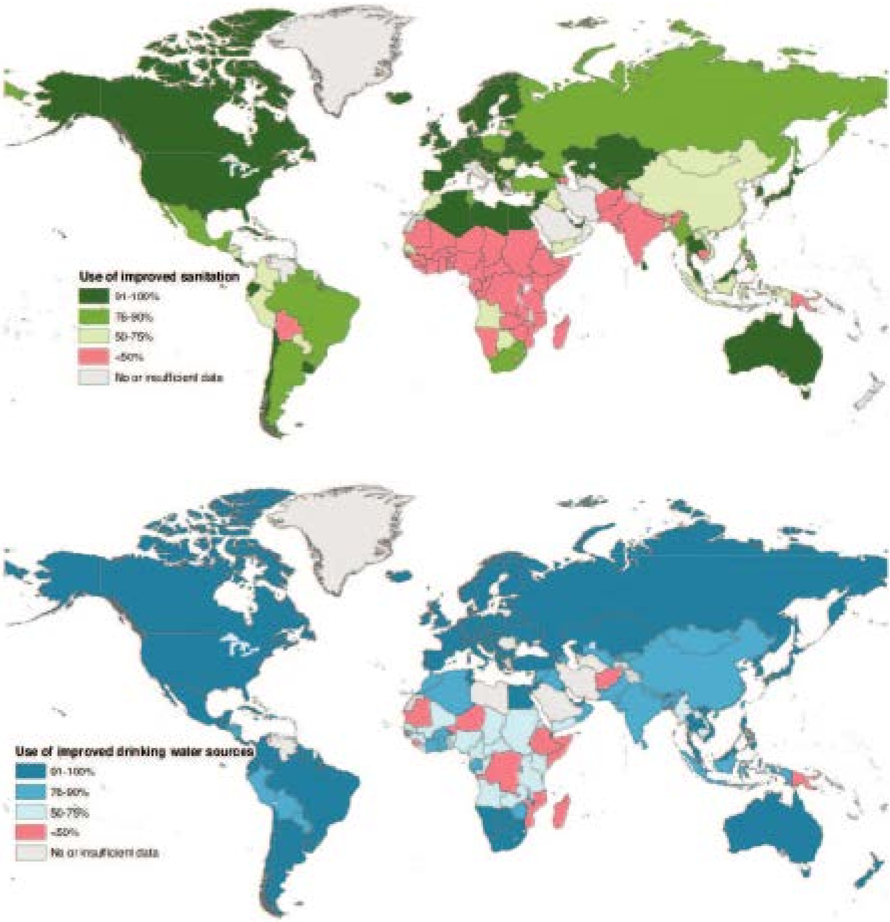

Figure 2:

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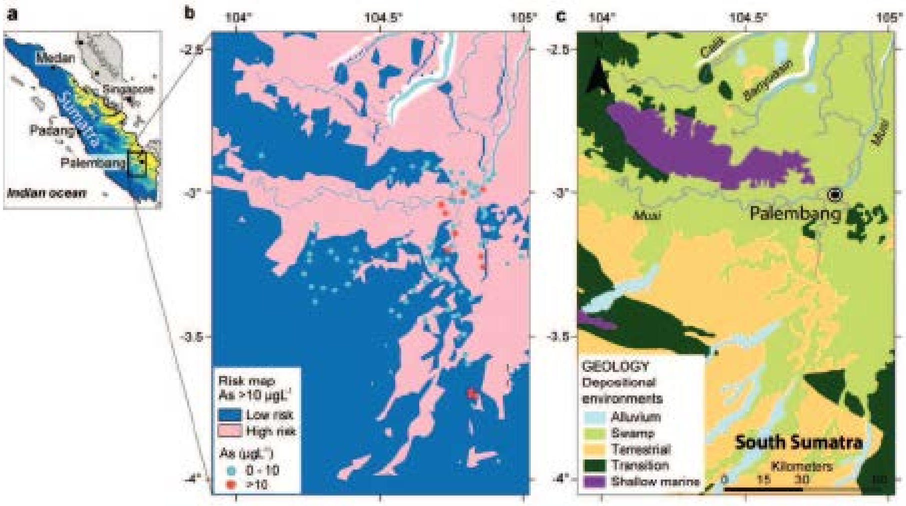

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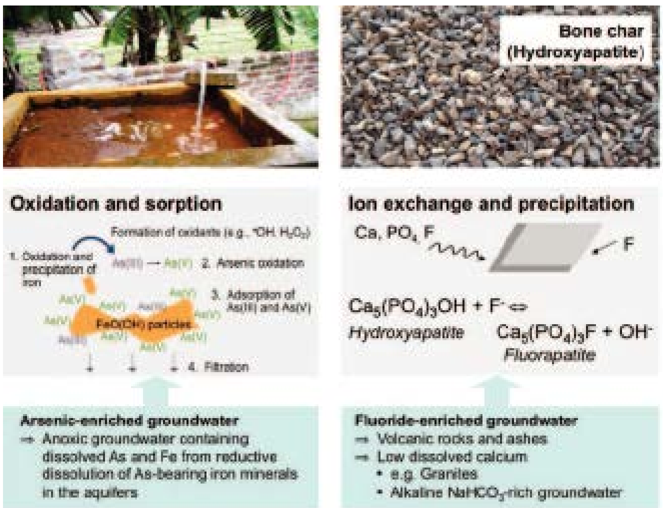

Figure 5: