

# Elemental Iron (Fe<sup>0</sup>) for Better Drinking Water in Rural Areas of Developing Countries

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**Abstract.** Many of the reasons behind the anthropogenic contamination problems in rural environments of developing countries lie in changes in the traditional way of life and the ignorance on the toxic potential of introduced manufactured products. A generalization trend exists within the international community suggesting that water in developing countries is of poor quality. However, the water quality is rarely analytically determined. Existing potabilization solutions may be prohibitively expensive for the rural populations. Therefore, efficient and affordable technologies are still needed to ameliorate the water quality. In the recent two decades, elemental iron has shown the capacity to remove all possible contaminants (including viruses) from the groundwater. This paper presents a concept to scale down the conventional iron barrier technology to meet the requirements of small communities and households in rural environments worldwide.

## Introduction

Water is essential to life and its quality is a major issue in sustainable development (Gadgil 1998). In humid areas of developing countries water problems are currently reported to be related more to quality preservation than to shortages (e.g., Brown 2007, Garcia 2007). Guidelines have been developed for maximum acceptable values for a number of contaminants in drinking water (WHO 2004). Specific guidelines are presented for acceptable concentrations of (i) bacteria, viruses, and parasites; (ii) chemicals of health significance including specific inorganic and organic constituents, pesticides, disinfectants, and disinfection by-products; (iii) radioactive constituents; and (iv) substances and parameters in drinking water that may give rise to complaints from consumers. Availability of plentiful and safe water for domestic use has long been known to be fundamental to the development process, with benefits spreading across all sectors, such as la-

bour productivity and obviously health sector. It has been shown that the most common and deadly pollutants in the drinking water in developing countries are of biological origin.

The population in the developing world suffers from six main diseases associated with water supply and sanitation (i) Diarrhea, (ii) *Ascaris*, (iii) *Dracunculiasis*, (iv) Hookworm, (v) *Schistosomiasis*, and (vi) Trachoma (Gadgil 1998, Sobsey et al. 2008). Many of the poorest people in developing countries must collect water outside the home and are responsible for treating and storing it themselves at the household level. This practice is a serious public health issue and has been addressed in the Millennium Development Goals, which aim to halve, by 2015, the proportion of people without access to safe water in 2000 (UN 2000). Looking toward the future, the water management must involve promoting improved international cooperation (Brown 2007, Micklin 1996).

One of the internationally recommended action to improve water management is water pricing. Water pricing is considered as a key tool: (i) to promote water use efficiency, (ii) to prevent water pollution, and (iii) to make for a more rational allocation of water (Micklin 1996, Sobsey et al. 2008). The idea behind water pricing is that the more one pays for water, the more careful he will use it. The more one must pay to pollute water, the less he will pollute. Economists have long advocated water pricing as helpful key to solve water resource use problems. For water pricing to be effective, water laws and institutions that inhibit formation of open water markets, have been reformed. Comprehensive and accurate water measuring system are currently established where it does not exist. At the end of the chain produced water should be affordable also for poor people, unless the goal of making potable water available could not be achieved. Thus, the question arises how sustainable is water pricing for developing countries?

Rural environments in developing countries have been reported to suffer from aching chemical pollution problems mostly from anthropogenic nature. Many of the reasons behind the chemical anthropogenic problems lie in changes in the traditional way of life and the ignorance on the toxic potential of recently introduced industrially manufactured products (Noubactep 2008a). Frequently, the sole available income generation activities (mining activities, intensive agriculture) are the source of water chemical pollution. Traditionally, there are three main sources of drinking water in rural areas: (i) rain water, (ii) surface water (spring, stream, river), and (iii) shallow groundwater (well). A recent development throughout the world is the installation of drilled wells with mechanic pumps. Drilled wells is considered as the best solution for bringing clean and quality water to surface. But the actual cost (about €6000 or US\$ 9500 each drilled well in Cameroon for example) is prohibitively expensive for many small communities. Therefore, the drinking water problem for developing countries is far from been solved. Ideally, all available water sources (rain water, surface water and shallow groundwater) should be treated on-side (at the point of use) such that even thirsty farmers, hunters can drink potable water far from their home.

The oldest and simplest method to produce potable water is to filtrate available water through a filter containing a non-toxic material. Ideally the filter material should be able to remove a large spectrum of contaminants (charged/uncharged,

organic/inorganic, living/non-living, reducible/non-reducible) and should be cost effective. It is very difficult to find a universal material which can be applied to the removal of a wide range of contaminants due to their very different chemical structures and molecular sizes. Fortunately, elemental iron (Fe<sup>0</sup>-bearing materials), a cost-effective and readily available material has shown the capacity to remove all possible contaminants (including biological contaminants – You et al. 2005) from the aqueous solution upon its oxidation (corrosion) during the past two decades. Elemental iron was originally introduced as filling material for subsurface reaction walls for groundwater remediation (Matheson and Tratnyek 1994, O'Hannesin and Gillham 1998).

The present work presents a concept to scale down the conventional iron barrier technology to meet the requirements of households and communities in rural environments worldwide. It is expected that elemental iron may be produced locally by rural communities while using old environmental friendly technologies of blacksmiths. Alternatively, construction steel and other Fe<sup>0</sup>-bearing materials (mild steel, cast iron) can be diverted from their intended use to serve as filter material for water treatment. In the following, some information on the quality of water in developing countries is first given. Then a survey of technologies for water treatment is presented, followed by an overview on the iron technology. In the last section, a discussion of the possibility of using the iron technology for ameliorating the quality of drinking water in developing countries is given.

## **A priori polluted Water**

A generalization trend exists within the international community suggesting that water in developing countries is of poor quality (e.g., Zimmerman et al. 2008). Thereby, despite remarkable progress in environmental instrumental analytical chemistry, the water quality is rarely determined. Clearly, the biochemical quality of the water that is drunk by billions of people worldwide is not known. Paradoxically, the western world (i) has developed standards for all known contaminants (nitrates, metals) and groups of contaminants (e.g., pesticides, radioactive species), and (ii) spends a lot of money on preserving wildlife or plant biodiversity in developing countries. The health of indigenous peoples that are currently struggling for survival in a permanently changing environment seems to be less important than that of exotic animals and plants. The majority of these indigenous peoples have shown a great preparedness to cope with the modern world, but have not received the adequate education to be trust to modern environmental challenges (Noubactep 2008a).

The belief that available water is of poor quality has been partly accepted and internalized by the large part of educated people in developing countries who are now seeking solutions to pollution in collaboration with partners worldwide. But how should a solution look like when the nature and the extent of contamination are not known? Another paradox of the belief of “a priori polluted water” is the fact that “Spring Water Companies” are currently supplying “pure”, natural spring

water (bottled water) to residents of industrialized countries. Thereby, the natural quality of “true flowing” springs, the mineral content, and the “natural taste” are three important features to justify elevated prices. Why should spring waters in the so-called third world be fundamentally of different quality?

The present work considers that the actual water quality is not known and proposes a concept for a safe and affordable technology to ameliorate the water quality in the case it may be polluted (precautionary principle). Before presenting the concept an overview over available treatment technology will be given, followed by a presentation of the elemental iron technology.

## Survey of technologies for water treatment

Water supply for human consumption has three primary objectives: (i) the minimisation of contamination of waters to be used as sources for drinking water; (ii) the reduction or removal of contaminants by means of treatment processes; and (iii) the prevention of contamination of the drinking water during distribution, storage and supply (Arnold and Colford 2007, Ram et al. 2007, WHO 2004). In developing countries natural waters are drunk mostly without treatment. These waters are certainly polluted at some sites. In particular in regions where poisonous geogenic species as arsenic are available. For these regions several low-cost point of use technologies have been proposed to protect live of indigenous peoples (Arnold and Colford 2007, Pokhrel et al. 2005, Ram et al. 2007, Ramaswami et al. 2001, Sobsey 2002, Sobsey et al. 2008). The supposedly simple, appropriate and affordable technologies suitable for rural areas with no electricity and no tap water have been mostly proposed in the frame work of international research projects.

The developed countries and international organizations have reported on providing substantial help to the developing world in meeting their pressing water needs (remember that the water quality is unknown as a rule). Technical assistance accompanied by massive infusions of capital is required to ensure universal access to clean drinking water. Beside the use of alternative water sources such as rain water harvesting, two currently proposed solutions are (Ramaswami et al. 2001): (a) On-site treatment in column systems packed with various adsorbents (including activated carbon and metal oxides) and reagents, e.g., iron, lime; (b) In-home treatment with alumina, iron, ferric chloride, and other reagents.

Brown (2007) recently reviewed “point of use” (POU) water treatment and safe storage technologies and their application in developing countries. Physical methods for small-scale water treatment include boiling, heating (using fuel and solar), filtering, settling, and ultraviolet (UV) radiation (solar or ultra violet lamps). Chemical methods include coagulation-flocculation and precipitation, ion exchange, chemical disinfection with germicidal agents (primarily chlorine), and adsorption. Combinations of these methods simultaneously or sequentially often yield promising results, for example coagulation combined with disinfection. Other combinations or multiple barriers are media filtration followed by chemical disinfection, media filtration followed by membrane filtration, or composite filtra-

tion combined with chemical disinfection. The review from Brown (2007) suggested that success of interventions is highly context specific, with no one technology or method representing a universal best solution. Availability of materials, quality of raw water available, cultural factors and preferences, or cost may determine where each of these is most suited to POU water treatment applications in developing countries (Sobsey 2002).

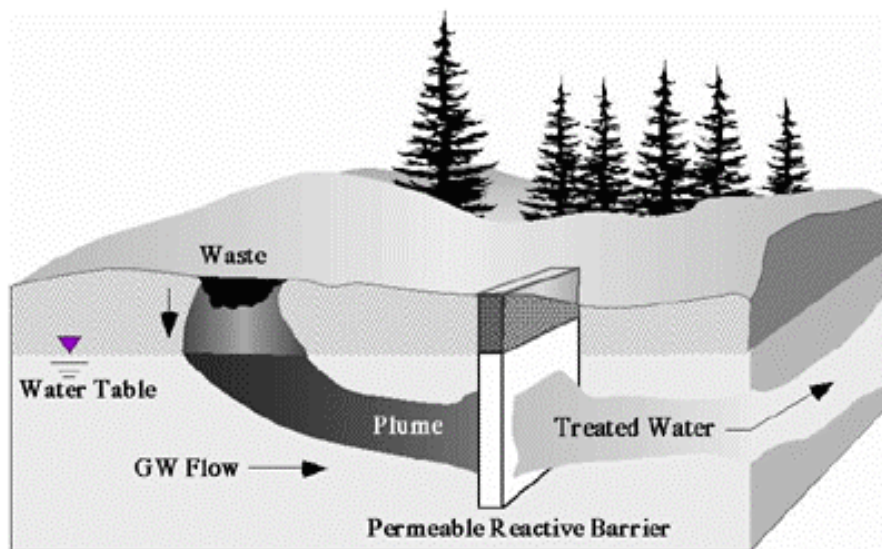
Appropriate point of use technologies for any water of unknown quality must meet certain criteria to be effective: (i) The technology must be effective over a wide range of contaminants, (ii) The technology must be simple to use, should not require running water or electricity, and be easily transferable to the users in their home. (iii) The materials need to be cheap, readily available and/or have a high reuse potential that would further reduce costs. (iv) Finally, any appropriate technology must be assessed to ensure that no other harmful chemicals are introduced into the water while the concerned contaminant is being removed.

Elemental iron is an appropriate material for point of use technologies. It has been already successfully tested in many regions of the world for arsenic removal (Karschunke et al. 2000, Ramaswami et al. 2001). Elemental iron has been successfully used to treat water contaminated with a variety of pollutants including fungicides, nitrates and pesticides. Furthermore, the mechanism of contaminant removal has been shown to be primarily non-specific, this makes Fe<sup>0</sup> an ideal material to treat water of unknown composition. Before presenting a concept to generalize the use of elemental iron as point of use material for rural areas of developing country, an overview on the iron technology will be given.

## The elemental iron technology

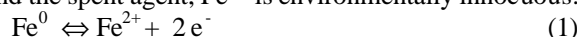
Permeable reactive barriers (PRBs) are a recent development of a passive system to remediate subsurface waters containing organic or inorganic contaminants. Contaminated groundwater flows under its natural gradient and passes through a permeable curtain (Fig. 1) of treatment medium that either (i) removes the contaminants from the aqueous phase by one or several mechanisms or (ii) transforms the contaminants into environmentally acceptable or benign species. The most widely adopted treatment medium is elemental iron (Fe<sup>0</sup>), a substance that is highly reactive, environmentally acceptable, and is readily available as a manufactured product derived from the recycling of scrap iron and steel. In cores of the reacted treatment media, the most abundant secondary product formed *in situ* is Fe oxyhydroxide (iron corrosion products – iron hydroxides and oxides), but a variety of precipitates has been identified. For example, secondary pyrite, greigite, covellite, chalcopyrite, and bornite have formed in the treatment medium (Jambor et al. 2005, Mackenzie et al. 1999). The secondary sulfides are volumetrically small and are unlikely to impede the permeability of the treatment medium, but the formation of Fe oxyhydroxides and secondary carbonates in the presence of Fe<sup>0</sup> requires further monitoring to determine whether the secondary precipitates and the consumption of Fe<sup>0</sup> will appreciably lessen the effectiveness of such PRBs over the

long term. Current indications are that PRBs are both an environmentally effective and a cost-effective technique of remediation (Henderson and Demond 2007, Jambor et al. 2005, Laine and Cheng 2007).



**Figure 1:** Illustration of a permeable reactive barrier remediating a plume (Source: [www.powellassociates.com](http://www.powellassociates.com)).

A trend persists in the scientific literature terming iron PRBs as a reduction technology (Kim et al. 2008, Laine and Cheng 2007) although contaminant reduction has not been traceably demonstrated. Elemental iron ( $\text{Fe}^0$ ) is a strong reducing agent (Eq. 1) and the spent agent,  $\text{Fe}^{2+}$  is environmentally innocuous.



When coupled with the reduction of a compound (e.g. an organic halide - R-X) the reaction should be spontaneous (Eq. 2):



Most investigators agree that the mechanism by which  $\text{Fe}^0$  remove reducible contaminants is by direct reduction at the iron surface. Other mechanisms have been proposed, including: (i) reduction by hydrogen, (ii) reduction by ferrous iron that is produced during the corrosion process, (iii) adsorption onto in-situ generated iron corrosion products. A few studies have shown that contaminant adsorption onto the  $\text{Fe}^0$  surface is an intermediate step towards reduction. The validity of these considerations has been challenged recently (Noubactep 2007, Noubactep 2008b). The major weak point of the “reductive transformation concept” is that it can not explain why non-reducible species (e.g., Zn, viruses) are quantitatively removed in  $\text{Fe}^0$ - $\text{H}_2\text{O}$  systems. An alternative concept was proposed considering adsorption and co-precipitation as primary mechanism of contaminant removal in  $\text{Fe}^0$ - $\text{H}_2\text{O}$  systems (Noubactep 2007).

The new concept takes the dynamic nature of the generation of iron corrosion products into account. Here, contaminant reduction by ferrous iron is an independent reaction path regardless from the external redox conditions and the electronic conductivity of the oxide film on iron. More importantly the new concept explains accurately why non-reducible pollutants and viruses are quantitatively removed in Fe<sup>0</sup>-H<sub>2</sub>O systems.

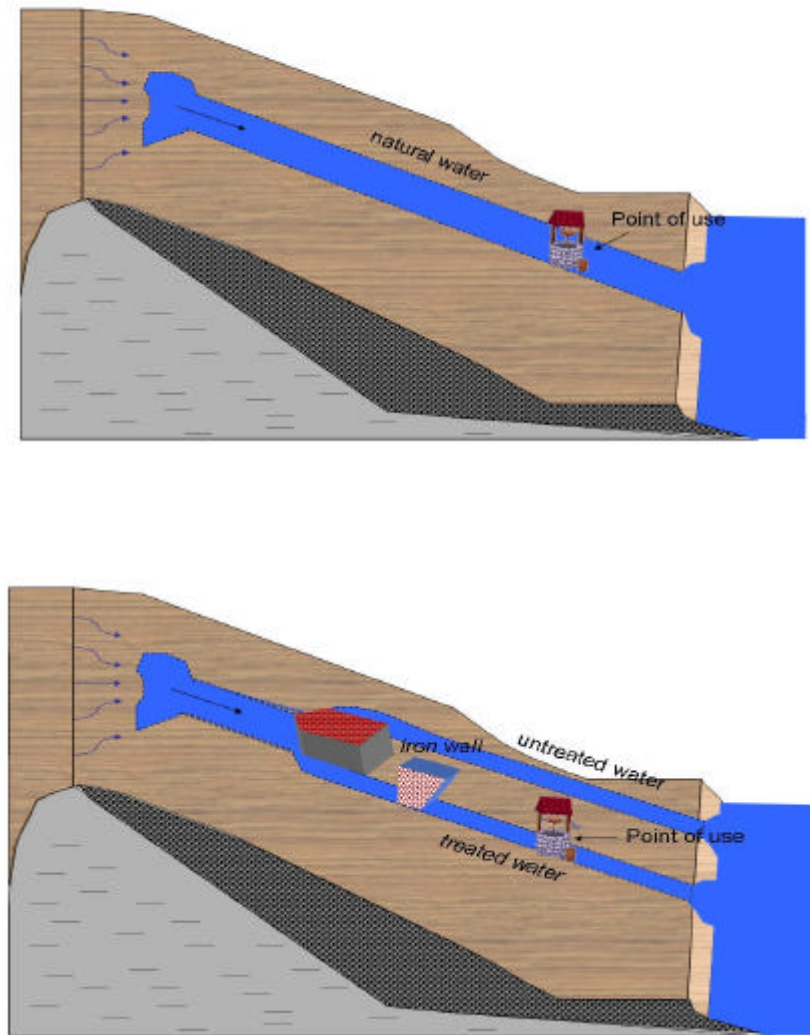
The long term feasibility of Fe<sup>0</sup> reactive barriers in the cleanup of contaminated groundwaters has been demonstrated in laboratory column studies and confirmed by field installations. Column studies and fields installations indicate that Fe<sup>0</sup> maintains its reactivity over long periods of time (Jambor et al. 2005). Many forms of iron have been proposed for water treatment. They differ in their size (nm, μm, mm), origin (scrap iron, by-products) and composition (cast iron, carbon steel, bimetallic). The next paragraph discusses how to use this technology to ameliorate the quality of drinking water in developing countries.

## **Iron technology for developing countries**

Considering adsorption and co-precipitation as the primary (initial or first step) removal mechanism of any species (ionic, neutral, organic, inorganic, and living) in the presence of elemental iron (e.g., in Fe<sup>0</sup>-H<sub>2</sub>O systems), Fe<sup>0</sup> is proposed as reactive medium for filters and small reactive walls for both on-side (well, source, river) and in-home (mostly rain) water treatment. The idea is to scale down reactive barrier for near-surface water treatment. Some features of subsurface reactive walls are still valid, in particular that the oxide-film primarily acts as contaminant scavenger. For reducible contaminants, direct or indirect reduction may still occur. An important difference is the increased availability of molecular oxygen at the surface. Long-term laboratory and field experiments are required to address this specific aspect.

As said above, the idea is not new but filters that had been proposed for water treatment at sites of specific chemical contamination is now proposed for worldwide use with two key differences: (i) the proposition is based on the latest scientific results (contaminant co-precipitation as primary removal mechanism), and (ii) filters and small reactive walls should be available everywhere where water is potentially drinkable even occasionally by hunters or travellers. Moreover biological and chemical contamination are both addressed.

To meet the ambitious goal of worldwide availability and cost-effectiveness, it should be avoided that populations have to buy special manufactured Fe<sup>0</sup> materials. For this purpose potential source of scrap iron should be identified and the material tested for their effectiveness. Alternatively, available Fe<sup>0</sup> materials for other intended purposes can be tested for use as water treatment material. Such Fe<sup>0</sup> materials are abundant in the construction industry (construction steel, reinforcing steel, wire).



**Figure 2:** Illustration of source management options: un-treated (up) and treated in an iron reactive wall (bottom). Whether the whole source flows through the barrier or not depends on the hydrodynamic conditions. The dimensioning of the branch through the reactive barrier will depend on the hydrodynamics, the characteristic of the used  $\text{Fe}^0$  material and the wished frequency of  $\text{Fe}^0$  replacement (e.g. once or twice a year).



Alternatively: (i) indigenous populations can be encouraged to produce steel by themselves while using environmental friendly technologies of their ancestors; (ii) Governments and NGOs (Non Government Organizations - sponsor) can purchase suitable Fe<sup>0</sup> materials.

The Fe<sup>0</sup> materials mixed with sand should serve as reactive material in in-home filters and in on-site small walls. In both cases layers of available adsorbents can be placed before the layer of Fe<sup>0</sup> to assure long-term reactivity of the filter/wall. On-site treatment units may be installed only on a natural or artificial branch of the available water source for economic purposes (Fig. 2). Intensive laboratory research is needed for a properly dimensioning of these units and to predict the frequency of material change.

The application of the results of these investigations will contribute to ameliorate the health of billions of people worldwide. A potential specific use of this technology is the adequate water supply for population (i) after a natural catastrophes (e.g. earthquake, Hurricane, Tsunami), (ii) in refugee camps over the world. Therefore, international organizations (FAO, WHO, Red Cross, NGOs) should be interested in the realization of this idea. There is no doubt that the successful application of the proposed concept will help to largely achieve the Millennium Development Goals (halving the proportion of people without access to safe water in 2000 by 2015).

## Acknowledgments

Christian Moeck (student research assistant) is kindly acknowledged for technical support. The work was partly supported by the Deutsche Forschungsgemeinschaft (DFG-No 626).

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