

Metallic iron filters for universal access to safe drinking water

(for CLEAN - Soil, Air, Water – Accepted 04-Sep-2009)

Noubactep Chicgoua^{*(1)}, Schöner Angelika⁽²⁾, Wofo Paul⁽³⁾

⁽¹⁾ Angewandte Geologie, Universität Göttingen, Goldschmidtstraße 3, D - 37077 Göttingen, Germany.

⁽²⁾ Institut für Geowissenschaften, Ingenieurgeologie, Martin-Luther-Universität Halle; Von-Seckendorff-Platz 3, D - 06120 Halle, Germany.

⁽³⁾ Laboratory of Modelling and Simulation in Engineering and Biological Physics, Faculty of Science, University of Yaounde I, Box 812 Yaounde, Cameroon

(*) corresponding author: cnoubac@gwdg.de; Tel. +49 551 39 3191, Fax: +49 551 399379.

Abstract

The availability of sustainable safe drinking water is one of Millennium Development Goals (MDGs). The world is on schedule to meet the MDG to “halve by 2015 the proportion of people without sustainable access to safe drinking water in 2000”. However, present technologies may still leave more than 600 million people without access to safe water in 2015. The objective of the present article is to present a concept for universal water filters primarily made of metallic iron (Fe^0) and sand. The concept of Fe^0 /sand filters is based on the combination of: (i) recent development of slow sand filtration and (ii) recent progress in understanding the process of contaminant removal in $\text{Fe}^0/\text{H}_2\text{O}$ systems. The filters should be made up of more than 60 % of sand and up to 40 % of Fe^0 . The actual Fe^0 proportion will depend on its intrinsic reactivity. The most important question to be answered regards the selection of the material to be used. The design of the filter can be derived from existing filters. It appears that $\text{Fe}^0/\text{H}_2\text{O}$ based filters could be a technology for the whole world.

Keywords: Contaminant removal, Point of use, Safe water, Water filtration, Zerovalent iron.

Acronym List

AMD	Acid mine drainage
BSF	Biosand filter
CIM	Composite iron matrix
EDTA	Ethylenediaminetetraacetate
KAF	Kanchan TM arsenic filters

30 MDG Millennium Development Goal

31 NGO Non-governmental organization

32 POU Point-of-use

33 ZVI Zerovalent Iron

34 **Introduction**

35 Naturally readily available waters (shallow groundwater; surface water, water from boreholes
36 and springs) are the main sources for drinking water production. These waters may become
37 contaminated with organic/inorganic chemical pollutants and pathogenic microorganisms
38 (bacteria, fungi, protozoa, viruses) from various origins: (i) natural (geogenic)
39 hydrogeochemical processes, (ii) artificial recharge with wastewater or water from septic
40 tanks or leaking sewage pipes, (iii) discharges of wastewater and/or manure run-off from
41 agricultural land.

42 To produce safe drinking water from natural waters, chemical pollutants and pathogens need
43 to be removed. One effective natural way is the passage of surface water through soil, as is
44 the case in bank filtration [1-4]. The effectiveness of bank filtration to produce safe drinking
45 water from natural waters depends on four major factors: (i) the extent of water pollution, (ii)
46 the nature of the soil, (iii) the thickness of the soil or the travel distance within the soil, and
47 (iv) the water flow rate or travel time. One can learn from nature and produce drinking water
48 at small scale. For this purpose, it can be assumed that for a sufficient amount of any relevant
49 treatment material in a filter, an adequate water flow rate will yield satisfactory contaminant
50 mitigation. The reactive material can be (i) a natural material, (ii) a synthetic material or
51 composites, or (iii) a mixture of materials. The material amount determines the thickness of
52 reactive layer in the filter. The water flow rate determines travel time.

53 During the past three decades, treating water at the household level has been shown to be one
54 of the most efficient means of preventing waterborne diseases world wide [5-10]. Here are six
55 examples for illustration: the use of (i) commercial filtration devices (e.g. Brita) mostly in

56 developed countries [11-13], (ii) ceramic pot filters or Kosim filters in Ghana [14], (iii) 3-
57 Kolshi filters and SONO filters in Bangladesh [6, 15, 16], (iv) Kanchan™ arsenic filters in
58 Nepal [17, 18], (v) Danvor plastic biosand filter [19], and (vi) Potters for Peace Filtron
59 ceramic filter [19,20]. Promoting household water treatment and safe storage helps
60 populations to actively take charge of their own water security. Therefore, providing people
61 with the knowledge and affordable tools to treat their own drinking water at the point of use is
62 a noble objective.

63 The present study aims at presenting a concept using metallic iron (Fe^0) as universal filter
64 material for water treatment at the point of use (POU) in general and at household level in
65 particular. The secondary objective is to demonstrate the suitability of Fe^0 for water treatment
66 in remote locations of developing countries. In these regions, available water could be
67 chemically safe (no geogenic or anthropogenic contamination). In this case, microbial
68 contamination due to lack of sanitation and improper hygiene is the sole source of water
69 contamination. Table 1 summarises some relevant water pathogens and related diseases [21].
70 The presentation is based on the state-of-the-art knowledge on the mechanism of contaminant
71 removal in the presence of Fe^0 ($\text{Fe}^0/\text{H}_2\text{O}$ systems) which will be presented first.

72 **Mechanisms of contaminant removal in $\text{Fe}^0/\text{H}_2\text{O}$ systems**

73 Passive remediation of water pollution by using $\text{Fe}^0/\text{H}_2\text{O}$ systems has been developed for
74 about 20 years [22-24]. Applications of these innovative systems included (i) groundwater
75 remediation, (ii) drinking water treatment, and (iii) wastewater treatment. Successful
76 quantitative removal of metals (e.g. Cd, Co, Cr, Cu, Pb, U, Zn), non-metals (e.g. As, Mo, Se,
77 Sn), anions (e.g. AsO_4^{3-} , F^- , MoO_4^{2-} , NO_3^- , PO_4^{3-} , SeO_4^{2-} , SO_4^{2-}), organic dyes, organic
78 compounds (e.g. benzene, chlorinated solvents, phenol, pesticides, toluene), bacteria,
79 suspended solids, and viruses has been reported [16, 25-30]. Almost all studies dealing with
80 pollutant removal were limited to proving the viability of $\text{Fe}^0/\text{H}_2\text{O}$ systems for a few target

81 pollutants and were not incorporated within a broad-based understanding of Fe^0 remediation
82 technology.

83 It is interesting to note that another technology, electrocoagulation [31-33], using Fe^0 , could
84 exhibit similar efficiency for a large spectrum of contaminants. Iron electrocoagulation can be
85 considered as an electrochemically driven accelerated corrosion process. In both cases
86 (passive $\text{Fe}^0/\text{H}_2\text{O}$ and iron electrocoagulation), pollutants are removed from water by a
87 multitude of mechanisms operating synergistically.

88 Likely removal mechanisms include: (i) adsorption onto Fe^0 and Fe oxides/hydroxides, (ii)
89 co-precipitation with Fe oxides (or co-precipitation on the substrate), (iii) direct reduction by
90 Fe^0 , (iv) indirect reduction by Fe^{II} or H/H_2 , (v) indirect oxidation by in situ generated radicals
91 $\text{HO}\cdot$. The exact sequence of these reactions depend on the system. Because redox-insensitive
92 pollutants have been quantitatively removed in passive $\text{Fe}^0/\text{H}_2\text{O}$ systems, any individual redox
93 process could not be the fundamental removal mechanism as originally assumed [23, 34].
94 Therefore, the fundamental mechanisms of contaminant removal in $\text{Fe}^0/\text{H}_2\text{O}$ systems are
95 adsorption (including surface complexation) and co-precipitation [35, 36].

96 Certainly, for some contaminants, such as Cr^{VI} which are reducible even in the aqueous phase
97 by Fe^{II} (under local anoxic conditions), quantitative reduction may precede adsorption and co-
98 precipitation. However, considering the nature of the $\text{Fe}^0/\text{H}_2\text{O}$ system, there is no reason to
99 consider quantitative reductive transformation a priori for some species. Moreover, a $\text{Fe}^0/\text{H}_2\text{O}$
100 system should be considered as zone of precipitating iron oxides/hydroxides [37]. During this
101 process expansive amorphous iron hydroxides are generated and further transformed by
102 dehydration to more crystalline oxides (Tab. 2) [38, 39].

103 **Diversity in the reactivity of iron oxides in $\text{Fe}^0/\text{H}_2\text{O}$ systems**

104 In order to better understand the role of metallic iron in Fe^0/sand filters, the dynamic nature of
105 iron corrosion in $\text{Fe}^0/\text{H}_2\text{O}$ systems will be discussed. For this purpose, synthetic bulk oxides
106 and oxide-films on Fe^0 should be compared in terms of reactivity towards contaminant

107 removal. Synthetic oxides and in situ formed oxide-films are fundamentally different in that
108 the latter are reactive systems (“reactive oxides”) by virtue of the continual generation and
109 annihilation of point defects at the interfaces. Furthermore, oxide-films (passive layers),
110 unlike synthetic oxides, continually grow into the metal at the Fe^0/layer interface while being
111 simultaneously destroyed by dissolution or restructuring at the layer/ H_2O interface [40, 41].
112 Accordingly, synthetic oxides are strictly “coatings” and hence, with respect to the processes
113 that influence Fe^0 reactivity, they are “dead” [40]. Synthetic oxides can only act as
114 contaminant adsorbents. Although synthetic oxides may be capable of simulating the
115 properties of the deposited outer layers (at the layer/ H_2O interface), it is difficult to see how
116 they can simulate the barrier layer (at the Fe^0/layer interface – “reactive oxides”), whose
117 defect concentration is normally far in excess of that which can be obtained in bulk oxides.
118 “Reactive oxides” are better adsorbents and may co-precipitate contaminants during their
119 formation and transformation to “dead oxides” [25, 35, 36, 42, 43]. “Dead oxides” are good
120 adsorbents of limited and selective affinity to some contaminants. The consequence of this
121 analysis is that Fe^0 can be regarded as a permanent source of highly reactive hydroxides
122 (“reactive oxides”) in a treatment system (statement 1). Statement 1 is the major argument on
123 which the concept of Fe^0/sand filters for universal access to safe drinking water is built.
124 A schematic illustration of the time-dependant evolution of iron corrosion products is given in
125 Figure 1. The cross-section of a spherical Fe^0 material experiencing uniform corrosion is
126 represented. It is assumed that the initial material (Fe^0 in Fig. 2) is progressively covered by
127 concentric layers of iron oxides from which the three most internal layers (d_1 , d_2 , d_3 , Fig. 2)
128 are “reactive” (see above) and all the external layers (d_4) are comparative in their reactivity to
129 synthetic bulk oxides (“coatings”). While this assumption is somewhat arbitrarily, d_1 can be
130 regarded as a layer of amorphous ferrous iron hydroxides ($\text{Fe}(\text{OH})_2$), d_2 a layer of mixed
131 amorphous iron hydroxides ($\text{Fe}(\text{OH})_2$ and $\text{Fe}(\text{OH})_3$), d_3 a layer of mixed amorphous iron

132 hydroxides/oxides (green rust, magnetite) and d₄ a layer of aged corrosion products
133 (crystallized iron oxides).

134 The schematic representations in Fig. 1 and 2 have intentionally neglected the expansive
135 nature of the process of iron oxide/hydroxide production from metallic iron [39, 44]. In fact,
136 the theoretical ratio ($\alpha_1 = V_{\text{oxide}}/V_{\text{Fe}}$) between the volume of corrosion products and the
137 volume of iron in the metallic structure varies between 2.0 for Fe₃O₄ and 6.4 for
138 Fe(OH)₃·3H₂O (Tab. 2). This volume increase is the principal cause of the expansion and
139 ultimately the loss of hydraulic conductivity (permeability loss) for remediation Fe⁰/H₂O
140 systems. Clearly, Fe⁰/sand filters end of service is not (or should not be) dictated by Fe⁰
141 depletion but rather by loss of hydraulic conductivity. The practical expansion of corrosion
142 products can be discussed from a proper kinetic law which correlates the radius loss of Fe⁰
143 and the corresponding volume of accumulated iron oxides [39]. In this work, mixing inert
144 sand and Fe⁰ is a practical tool to extend filter service life. It is expected that for any
145 appropriate Fe⁰ material, an optimal weight ratio sand/Fe⁰ should exist for satisfactorily water
146 treatment in the medium or long term (e.g. ≥ 12 months).

147 **Water treatment by sand filtration**

148 Promising strategies for providing people with access to safe water are available, but may not
149 be suitable/affordable for areas of low population density with little perspective for economic
150 growth (e.g. rural areas, [45, 46]). It may further prove challenging to guarantee the quality of
151 drinking water in these populations. Methods that allow the treatment of the water at the place
152 where it is consumed (POU methods) may provide a low-cost, promising, easy and flexible
153 solution for increasing drinking water quality in much of the population in need. Slow sand
154 filtration is one of these methods.

155 **Basic sand filtration**

156 The earliest form of water treatment was slow sand filtration. Slow sand filters were
157 developed in the 1820's in Scotland by Robert Thom and in England by James Simpson. They

158 became successfully established in Europe by the end of the 19th century [47-50]. This
159 technology used sand filter beds through which water is slowly trickled. The natural
160 formation of a biological layer (biofilm, widely termed as Schmutzdecke) and the filtering
161 action of sand removes bacteria, silt and chemical pollutants. The treatment efficiency is
162 affected partly by physical straining but more importantly by biological action within the
163 biofilm that formed on top of the sand [51]. A household-scale intermittent slow sand filter
164 (the Davnor Biosand filter or Davnor BSF) developed by Manz has been successfully tested
165 by several governments, research and health institutions and NGOs in Bangladesh, Brazil,
166 Canada, Haiti, Nicaragua, Vietnam and other countries [52, 53]. Lantagne et al. [5]
167 summarized the drawbacks of the BSF as follows: (i) low rate of virus inactivation, (ii) lack
168 of residual protection and removal of less than 100 percent of the bacteria, which leads to
169 recontamination, (iii) current lack of studies proving health impact, and (iv) difficulty in
170 transport and high initial cost, which make scalability more challenging. Accordingly the
171 major problem with BSF is that complete pathogen removal can not be guaranteed. Therefore,
172 if water can be successfully freed from pathogens within a sand filter, this technology can be
173 used with more confidence for safe drinking water at a household level. The presentation on
174 the mechanisms of contaminant removal in $\text{Fe}^0/\text{H}_2\text{O}$ systems suggests that coupling reactive
175 Fe^0 to sand could solve the problem (statement 1). This work has already been done but Fe^0
176 aimed at eliminating arsenic as presented below.

177 **Improved sand filtration**

178 Recently, the Arsenic Biosand Filter (KanchanTM Arsenic Filter - KAF) was developed and
179 distributed in Nepal by Ngai et al. [17, 18]. The KAF is built on the platform of a slow sand
180 filter, modified to include/increase arsenic removal capability. The KAF combines the
181 concepts of slow sand filtration and an intermittent household-scale system with the
182 innovation of a diffuser basin containing iron nails for arsenic removal. In the KAF, arsenic is
183 certainly quantitatively removed by adsorption onto or by co-precipitation with iron

184 oxyhydroxides from rusting iron nails. Pathogens (e.g. bacteria) have been reported to be
185 removed mostly by physical straining provided by the fine sand layer, by attachment to
186 previously removed particles and, to a lesser degree, by biological predation occurring in the
187 top few centimeters of the sand. The KAF was demonstrated successful for simultaneous
188 arsenic and pathogen removal and is considered as the best among all household arsenic
189 filters available in Nepal [18]. Chiew et al. [54] have recently published primary results on
190 attempts to extend the concept of KAF filtration in Cambodia (Fig. 3).

191 Recent developments in the understanding of the process of contaminant removal in $\text{Fe}^0/\text{H}_2\text{O}$
192 systems demonstrates that pathogens are certainly removed/inactivated by co-precipitation
193 with iron oxyhydroxides from a rusting Fe^0 . Therefore, a further development of the
194 KanchanTM Arsenic Filter is to disseminate Fe^0 in of the “pathogen removal unit” of the filter
195 (BioSand filter – Fig. 2) or to replace the “arsenic removal unit” by a water saturated Fe^0 /sand
196 layer. The second possibility is discussed below. Such a filter will remove all possible
197 contaminants (including arsenic and bacteria) from the aqueous solution.

198 **Fe^0 /sand filters**

199 The works of Dr. Manz yielded an efficient intermittent household-scale slow sand filtration
200 system for “safe” drinking water [50]. Ngai et al. [18] further developed this system by
201 adding small amount of metallic iron to optimize arsenic (and pathogen) removal. As a rule
202 the nature and extent of water contamination in rural areas of developing countries is
203 unknown [46]. However, despite the variability of the influents the system outputs have to be
204 satisfactory. Based on the state-of-the-art knowledge on the mechanism of contaminant
205 removal by $\text{Fe}^0/\text{H}_2\text{O}$ systems, the used of metallic iron as universal material for safe drinking
206 water has been suggested [55, 56]. The works of Ngai et al. [18] suggested that the amount of
207 Fe^0 in the filter is not necessarily high (e.g. 10 % weight). Furthermore, since chemical
208 contaminants and pathogens are certainly co-precipitated with precipitating iron corrosion
209 products, the flow rate of contaminated waters through the Fe^0 /sand filter can be enhanced to

210 reach the daily demand of individual families within a few tens of minutes. That is the idea
211 behind Fe⁰/sand filters.

212 **The innovation in Fe⁰/sand filters**

213 People familiar with the problematic of arsenic contamination in Bangladesh and Nepal are
214 aware that an effective Fe⁰/sand filtration system (3-Kolshi system) was abandoned because
215 of loss of porosity of the system. A close look of the 3-Kolshi filtration system reveals that the
216 top Kolshi was filled with 3 kg of cast iron and 2 kg of sand on top of the iron turnings [15].
217 In other words the Kolshi with Fe⁰ (here cast iron) contains a zone of 100 % Fe⁰ overlying the
218 sand layer. The 3-Kolshi filtration system was replaced by the SONO filter. Here, the primary
219 active material is a porous composite iron matrix (CIM), a mass made of cast iron turnings
220 through a proprietary process to maintain active CIM integrity for years [6, 16]. Again a 100
221 % layer of composite is sandwiched between two layers of (coarse) sand. The reported loss of
222 porosity is necessarily coupled to the too high proportion of Fe⁰ in the reactive zone (actually
223 100 %). Given the relative low concentration of arsenic in contaminated waters, this huge
224 amount of Fe⁰ (and possibly composite) is obviously unnecessary. As discussed above Fe⁰
225 depletion should not occur. However, even the KAF of Ngai et al. [18] contains a 100 % layer
226 of iron nails at the top of fine sand, coarse sand and gravel. The relative amount of iron nails
227 in KAF was small compared to that of reactive materials in 3-Kolshi and SONO filtration
228 systems and the KAF are efficient for several years [17]. Therefore, reducing the proportion
229 of Fe⁰ in the system is a sensible modification to maintain filter permeability for a long time.
230 The real novelty with the proposed Fe⁰/sand filters is that no 100 % Fe⁰ will be available.
231 Rather, the Fe⁰ reactive layer will be a mixture of at least 60 % sand, gravel or porous
232 volcanic rocks and up to 40 % Fe⁰. The actual proportion of the Fe⁰ will depend on its
233 intrinsic reactivity and particle size. The advantage of porous volcanic rocks [57-59] is that
234 generated iron hydroxides may fill their porous structure extending service life (or retarding
235 loss of hydraulic conductivity). On the other hand, Fe⁰ materials could be produced locally

236 [60-63] or selected from available iron products (including production wastes and by-
237 products) such as nails rivets, nuts, bolts, barbed wire, packing wire, chicken wire mess,
238 fencing wire, steel wool, construction materials and other Fe^0 products. Using available Fe^0
239 materials will protect filter users from the market law as increased demand is only indirectly
240 coupled to the original use of the material. For example, it can not be expected that the price
241 of packing wire increases just because it is used for water treatment. Another approach will
242 consist of testing potential Fe^0 materials in industrialised countries (including China), that are
243 likely exported to developing countries and built a database for suitable materials.

244 **Potential beneficiaries of Fe^0 /sand filters**

245 It is certain that Fe^0 /sand filters will accelerate the health gains associated with improved
246 drinking water until the goal of universal access to piped, treated water is achieved [5]. Even
247 after this hypothetical goal is achieved, the world will still have to face critical situations (e.g.
248 accidental contamination, earthquakes, epidemic plagues, wars, tsunamis), in which available
249 water should be rapidly treated. These critical situations are managed worldwide mostly by
250 armies and NGOs (including the Red Cross). Therefore, the Fe^0 /sand filters are not only
251 suitable for developing countries but for the whole world. Recently, an uranium
252 contamination was discovered in drinking water production wells in Barlissen in Lower
253 Saxony/Germany and the wells were precautionary put out of service [64]. Barlissen is a
254 typical situation where Fe^0 /sand filters could help in industrialized countries.

255 On the other hand, working on Fe^0 /sand filters will give researchers from developing
256 countries the opportunity to solve a crucial problem with local solutions. The technology is
257 low cost and good results can be achieved with simple equipment. Furthermore, experiments
258 do not involve any stringent reaction conditions nor expensive devices, as the major
259 experiments are to be conducted under atmospheric conditions. It is expected that research
260 groups working on Fe^0 /sand filters will achieve results which are helpful for the further
261 development of iron reactive walls. In fact, Fe^0 /sand filters can be regarded as a sort of “rapid

262 small scale column test” which could help to bridge the gap between short-term studies in the
263 lab (few weeks) and field Fe⁰ reactive barriers (some two decades). In fact, testing Fe⁰/sand
264 filters offers a unique opportunity to test the reactivity of the same Fe⁰ material at several sites
265 with natural waters of various characteristics. Clearly, a South/North symbiosis can be
266 expected: a technology developed in the North tested and used in a modified version in the
267 South could contribute to the further development of the original technology (not only for the
268 North).

269 **Ways to affordable Fe⁰/sand filters**

270 The concept of Fe⁰/sand filters is based on scientific understanding of the complex chemical
271 and physical processes involved in an evolving technology (iron remediation technology) that
272 has being successfully applied for almost 20 years. Provided that a relevant reactive Fe⁰ is
273 used, the effectiveness of Fe⁰/sand filters is not to be demonstrated, except some technology
274 verification in the field (monitoring). The sole tasks are: (i) selecting and processing the
275 appropriate Fe⁰ materials, (ii) designing the filters, and (iii) avoiding the use of Fe⁰/sand
276 filters for waters of pH ≤ 5. In fact, Fe⁰/sand filters are based on the anodic dissolution of iron
277 in neutral and close-to-neutral aqueous systems. In this pH range, primary iron dissolution is
278 followed by a continuous build up and transformation of a corrosion product layer in the
279 vicinity of Fe⁰ [41, 65, 66].

280 **Material selection**

281 Practically any available Fe⁰ material (mainly low alloyed steel and cast iron) is theoretically
282 applicable for water treatment. Ideally, any newly obtained Fe⁰ material should be
283 characterized and tested for water treatment capacity by a standard method. In using activated
284 carbon for wastewater treatment for example, it is generally accepted that a good decolorizing
285 carbon should fulfil at least 200 mg/g removal capacity for methylene blue in batch
286 experiments [67]. Until recently, there was no experimental parameter to characterize the
287 intrinsic reactivity of Fe⁰ materials [68-70]. Noubactep [69, 70] has introduced a parameter,

288 k_{EDTA} , which could enable purposeful material selection. Per definition, k_{EDTA} is the slope of
289 the line of the time-dependent oxidative dissolution of iron from a given Fe^0 material in a 2
290 mM EDTA solution. k_{EDTA} is determined in batch experiments and characterized material
291 intrinsic reactivity under any given experimental conditions [70]. For example, materials used
292 in Fe^0 /sand filters should exhibit a k_{EDTA} value above a critical value. This critical value is yet
293 to be determined. The k_{EDTA} value of the iron nails used by Ngai et al. [18] could be used as
294 guide to select the Fe^0 loading of the filter. For a less reactive material a larger Fe^0 loading
295 than in the KanchanTM Arsenic Filter will be applied and lesser Fe^0 loadings are needed for
296 more reactive materials. The long term reactivity of available Fe^0 materials has to be tested as
297 well. Initially, iron nails from the KAF filters or iron composites from the SONO filters can
298 be used as starting point.

299 **Filter designs**

300 Basically, Fe^0 /sand filters are slow sand filters for intermittent use [49, 50]. Almost 130 years
301 of experience is available for this type of system. The most recent developments are those of
302 KanchanTM Arsenic Filter [18], SONO filters [6, 16] and Kosim filters [14]. These devices
303 can be modified to use a Fe^0 /sand reactive layer as described above. Alternatively, new
304 designs may be conceived based on local specifications [71]. Fig. 3 shows a cross-section of
305 the filter design used by Chiew et al. [54]. Arsenic removal and bacterial removal units are
306 illustrated. A potential shortcoming of this design is that the "arsenic removal unit"
307 experiences wet and dry periods. In an improved design, the high of the outlet pipe should
308 enable immersion of the Fe^0 layer.

309 In all cases the filters should be constructed from local materials and the reactive layer should
310 be embedded in sand layers. Available Fe^0 materials (e.g. iron nails, steel wool) should be
311 tested and approved at least in the early stage of technology implementation. The Fe^0 /sand
312 filter should be manufactured locally by trained workers regardless of their scholar education.

313 To sustain the Fe^0 reactivity, intermittent additions (e.g. once a month) of boiled water [16] or
314 lemon juice [72] could be envisaged.

315 While Hussam and Munir [16] used boiled water to eventually kill pathogens, the present
316 review demonstrated that upon purposeful dimensioning, pathogens will be sequestered by
317 iron corrosion products. Therefore, boiled water should increase/sustain Fe^0 reactivity by
318 elevating the temperature. Intermittent temperature elevation certainly disturb the process of
319 iron passivation, and thus sustain Fe^0 reactivity as reported by Hussam and Munir [16].

320 The rational for the use of citric acid is the well-known increase iron corrosion with
321 decreasing pH value [65, 66]. Cornejo et al. [72] tested three commercially available lemon
322 species as citric sources. Commercial lemon species may content undesirable preservatives
323 and little parts of fruit. Even though these undesirable contents are non toxic, these additives
324 should be regarded as contaminants and will be removed in the filtering system as well. In
325 rural areas natural lemon juice should be at least seasonally available at low cost or cheaper
326 than commercial lemon juices. While testing the ability of citric acid ($\text{pK}_{\text{a}1} = 3.15$, $\text{pK}_{\text{a}2} =$
327 4.77 , $\text{pK}_{\text{a}3} = 6.40$) to sustain reactivity, care will be taken to keep the $\text{pH} > 4.5$ to avoid
328 dissolved Fe in filtered water. Again, this technology is not applicable for the treatment of
329 waters of initial $\text{pH} < 5$. Such waters, known as from acid mine drainage (AMD) are world
330 wide available at abandoned and active mining sites [73].

331 **Conclusions**

332 The fact that field $\text{Fe}^0/\text{H}_2\text{O}$ systems have successfully removed various contaminants from
333 polluted water is a testament to their potential, which is yet to be fully realized. This paper
334 presents a concept to realize this potential at a household level by a simple water filtration on
335 a Fe^0/sand column. The Fe^0/sand filter is an innovation combining two proven water treatment
336 techniques: (i) adsorption and co-precipitation in $\text{Fe}^0/\text{H}_2\text{O}$ systems, and (ii) size exclusion by
337 slow sand filtration. There is no doubt that a proper material selection and design of the
338 filtration system will contribute to achieve and even exceed the Millennium Development

339 Goal. The original merit of this concept is that it allows researchers from developing countries
340 to actively work on a crucial problem while results will be useful for the developed world as
341 well. Intensive laboratory and field research is needed to develop Fe⁰/sand filters. The efforts
342 should be accompanied by numerical modeling. This aspect is under investigation in the
343 research group of one of the authors (P. Woafu) using mathematical equations describing the
344 spatio-temporal evolution of pollutants concentration and porosity in the filters complemented
345 by experiments. On the other hand, reportedly efficient filters (e.g. Danvor BSF, Filtron
346 ceramic filter, Kosim filter) can be amended with Fe⁰ to enhanced pathogen inactivation.

347 **Acknowledgments**

348 Thoughtful comments provided by Prof. Abul Hussam (Center for Clean Water and
349 Sustainable Technologies, George Mason University - USA) on the draft manuscript are
350 gratefully acknowledged. Sven Hellbach (student research assistant) is acknowledged for
351 technical assistance. The manuscript was improved by the insightful comments of anonymous
352 reviewers from CLEAN Soil, Air, Water.

353 **Conflict of Interest**

354 The authors have declared no conflict of interest.

355 **References**

- 356 [1] J.F. Schijven, S.M. Hassanizadeh, Removal of viruses by soil passage: Overview of
357 modeling, processes, and parameters. *Crit. Rev. Environ. Sci. Technol.* **2000**, 30 (1),
358 49.
- 359 [2] K.M. Hiscock, T. Grischek, Attenuation of groundwater pollution by bank filtration. *J.*
360 *Hydrol.* **2002**, 266 (3-4), 139.
- 361 [3] S. Grünheid, G. Amy, M. Jekel, Removal of bulk dissolved organic carbon (DOC) and
362 trace organic compounds by bank filtration and artificial recharge. *Water Res.* **2005**,
363 39 (14), 3219.

- 364 [4] W.J. Weiss, E.J. Bouwer, R. Aboytes, M.W. LeChevallier, C.R. O'Melia, B.T. Le, K.J.
365 Schwab, Riverbank filtration for control of microorganisms: Results from field
366 monitoring. *Water Res.* **2005**, 39 (10), 1990.
- 367 [5] D.S. Lantagne, R. Quick, E.D. Mintz, Household water treatment and safe storage options
368 in developing countries: A review of current implementation practices. In *Water*
369 *Stories: Expanding Opportunities in Small-Scale Water and Sanitation Projects*, **2006**,
370 pp 17–38.
- 371 [6] S. Ahamed, A.K.M. Munir, A. Hussam, in *Handbook of Water Quality and Water Purity*,
372 Elsevier Inc., **2008**, Chapter 16, 379.
- 373 [7] M.D. Sobsey, C.E. Stauber, L.M. Casanova, J.M. Brown, M.A. Elliott, Point of use
374 household drinking water filtration: A practical, effective solution for providing
375 sustained access to safe drinking water in the developing world. *Environ. Sci.*
376 *Technol.* **2008**, 42 (12), 4261.
- 377 [8] T. Clasen, J. Bartram, J. Colford, S. Luby, R. Quick, M. Sobsey, Comment on “Household
378 Water Treatment in Poor Populations: Is There Enough Evidence for Scaling up
379 Now?” *Environ. Sci. Technol.* **2009**, 43 (14), 5542.
- 380 [9] W.-P. Schmidt, S. Cairncross, Household water treatment in poor populations: Is there
381 enough evidence for scaling up now? *Environ. Sci. Technol.* **2009**, 43 (4), 986.
- 382 [10] W.-P. Schmidt, S. Cairncross, Response to comment on “Household Water Treatment in
383 Poor Populations: Is There Enough Evidence for Scaling up Now?” *Environ. Sci.*
384 *Technol.* **2009**, 43 (14), 5545.
- 385 [11] F.D. Daschner, Holy water, tap water, mineral water or water filters? *J. Hospital Infect.*
386 **1997**, 35 (1), 71.
- 387 [12] B.L. Gulson, A. Sheehan, A.M. Giblin, M. Chiaradia, B. Conradt, The efficiency of
388 removal of lead and other elements from domestic drinking waters using a bench-top
389 water filter system. *Sci. Tot. Environ.* **1997**, 196 (3), 205.

- 390 [13] S. Levesque, M.J. Rodriguez, J. Serodes, C. Beaulieu, F. Proulx, Effects of indoor
391 drinking water handling on trihalomethanes and haloacetic acids. *Water Res.* **2006**, 40
392 (15), 2921.
- 393 [14] S.M. Johnson, R.L. Peletz, S. Murcott, Results from household ceramic filter evaluation
394 in northern Ghana. In 33rd WEDC International Conference Accra, Ghana, **2008**, 463.
- 395 [15] A.K.M. Munir, S.B. Rasul, M.A. Habibuddowla, M.A. Hussam, A.H. Khan, Evaluation
396 of Performance of Sono 3-Kolshi Filter for Arsenic Removal from Groundwater Using
397 Zero Valent Iron Through Laboratory and Field Studies. In Proceedings International
398 Workshop on Technology for Arsenic Removal from Drinking Water, Bangladesh
399 University of Engineering and Technology and United Nations University, Japan, May
400 5, 2001. **2001** pp. 171-189.
- 401 [16] A. Hussam, A.K.M. Munir, A simple and effective arsenic filter based on composite iron
402 matrix: Development and deployment studies for groundwater of Bangladesh. *J.*
403 *Environ. Sci. Health A* **2007**, 42 (12), 1869.
- 404 [17] T.K.K. Ngai, S. Murcott, R.R. Shrestha, B. Dangol, M. Maharjan, Development and
405 dissemination of Kanchan™ Arsenic Filter in rural Nepal, *Water Sci. Technol. Water*
406 *Supply* **2006**, 6 (3), 137–146.
- 407 [18] T.K.K. Ngai, R.R. Shrestha, B. Dangol, M. Maharjan, S.E. Murcott, Design for
408 sustainable development—Household drinking water filter for arsenic and pathogen
409 treatment in Nepal. *J. Environ. Sci. Health A* **2007**, 42 (12), 1879.
- 410 [19] J. Baumgartner, S. Murcott, M. Ezzati, Reconsidering ‘appropriate technology’: the
411 effects of operating conditions on the bacterial removal performance of two household
412 drinking-water filter systems. *Environ. Res. Lett.* **2007** 2, 024003.
- 413 [20] D. van Halem, H. van der Laan, S.G.J. Heijman, J.C. van Dijk, G.L. Amy, Assessing the
414 sustainability of the silver-impregnated ceramic pot filter for low-cost household
415 drinking water treatment. *Phys. Chem. Earth* **2009**, 34 (1-2), 36.

- 416 [21] R. Hoffman, M.M. Marshall, M.C. Gibson, P.A. Rochelle, Prioritizing Pathogens for
417 Potential Future Regulation in Drinking Water. *Environ. Sci. Technol.* **2009**, 43 (14),
418 5165.
- 419 [22] R.W. Gillham, S.F. O'Hannesin, Enhanced degradation of halogenated aliphatics by
420 zero-valent iron. *Ground Water* **1994**, 32 (6), 958.
- 421 [23] L.J. Matheson, P.G. Tratnyek, Reductive dehalogenation of chlorinated methanes by iron
422 metal. *Environ. Sci. Technol.* **1994**, 28 (12), 2045.
- 423 [24] S.F. O'Hannesin, R.W. Gillham, Long-term performance of an in situ "iron wall" for
424 remediation of VOCs. *Ground Water* **1998**, 36 (1), 164.
- 425 [25] S.L.S. Stipp, M. Hansen, R. Kristensen, M.F. Hochella Jr., L. Bennedsen, K. Dideriksen,
426 T. Balic-Zunic, D. Léonard, H.-J. Mathieu, Behaviour of Fe-oxides relevant to
427 contaminant uptake in the environment. *Chem. Geol.* **2002**, 190 (1-4), 321.
- 428 [26] Y. You, J. Han, P.C. Chiu, Y. Jin, Removal and inactivation of waterborne viruses using
429 zerovalent iron. *Environ. Sci. Technol.* **2005**, 39 (23), 9263.
- 430 [27] A.D. Henderson, A.H. Demond, Long-term performance of zero-valent iron permeable
431 reactive barriers: a critical review. *Environ. Eng. Sci.* **2007**, 24 (4), 401.
- 432 [28] A.B. Cundy, L. Hopkinson, R.L.D. Whitby, Use of iron-based technologies in
433 contaminated land and groundwater remediation: A review. *Sci. Tot. Environ.* **2008**,
434 400 (1-3), 42.
- 435 [29] R. Thiruvengkatachari, S. Vigneswaran, R. Naidu, Permeable reactive barrier for
436 groundwater remediation. *J. Ind. Eng. Chem.* **2008**, 14, 145.
- 437 [30] R.L. Johnson, R.B. Thoms, R.O'B. Johnson, T. Krug, Field evidence for flow reduction
438 through a zero-valent iron permeable reactive barrier. *Ground Water Monit. Remed.*
439 **2008**, 28 (3), 47.
- 440 [31] M.Y.A. Mollah, R. Schennach, J.R. Parga, D.L. Cocco, Electrocoagulation (EC) –
441 science and applications, *J. Hazard. Mater.* **2001**, 84 (1), 29.

- 442 [32] D. Lakshmanan, D.A. Clifford, G. Samanta, Ferrous and ferric ion generation during iron
443 electrocoagulation. *Environ. Sci. Technol.* **2009**, 43 (10), 3853.
- 444 [33] C.H.A. Moreno, D.L. Cocke, J.A.G. Gomes, P. Morkovsky, J.R. Parga, E. Peterson, C.
445 Garcia, Electrochemical reactions for electrocoagulation using iron electrodes. *Ind.*
446 *Eng. Chem. Res.* **2009**, 48 (4), 2275.
- 447 [34] E.J. Weber, Iron-mediated reductive transformations: investigation of reaction
448 mechanism. *Environ. Sci. Technol.* **1996**, 30 (2), 716.
- 449 [35] C. Noubactep, Processes of contaminant removal in “Fe⁰-H₂O” systems revisited. The
450 importance of co-precipitation. *Open Environ. J.* **2007** 1 (1), 9.
- 451 [36] C. Noubactep, A critical review on the mechanism of contaminant removal in Fe⁰-H₂O
452 systems. *Environ. Technol.* **2008a**, 29 (8), 909.
- 453 [37] C. Noubactep, An analysis of the evolution of reactive species in Fe⁰/H₂O systems. *J.*
454 *Hazard. Mater.* **2009a**, 168 (2-3), 1626.
- 455 [38] R. Balasubramaniam, A.V.R. Kumar, P. Dillmann, Characterization of rust on ancient
456 Indian iron. *Curr. Sci.* 2003, 85 (11), 1546.
- 457 [39] S. Caré, Q.T. Nguyen, V. L'Hostis, Y. Berthaud, Mechanical properties of the rust layer
458 induced by impressed current method in reinforced mortar. *Cement Concrete Res.*
459 **2008**, 38 (8-9), 1079.
- 460 [40] E. Sikora, D.D. Macdonald, The Passivity of Iron in the Presence of
461 Ethylenediaminetetraacetic Acid I. General Electrochemical Behavior. *J. Electrochem.*
462 *Soc.* **2000**, 147 (11), 4087.
- 463 [41] P. Schmucki, From Bacon to barriers: a review on the passivity of metals and alloys. *J.*
464 *Solid State Electrochem.* **2002**, 6 (3), 145.
- 465 [42] R.J. Crawford, I.H. Harding, D.E. Mainwaring, Adsorption and coprecipitation of single
466 heavy metal ions onto the hydrated oxides of iron and chromium. *Langmuir* **1993a**, 9
467 (11), 3050.

- 468 [43] R.J. Crawford, I.H. Harding, D.E. Mainwaring, Adsorption and coprecipitation of
469 multiple heavy metal ions onto the hydrated oxides of iron and chromium. *Langmuir*
470 **1993b**, 9 (11), 3057.
- 471 [44] K. Bhargava, A.K. Ghosh, Y. Mori, S. Ramanujam, Modeling of time to corrosion
472 induced cover cracking in reinforced concrete structures. *Cement Concrete Res.* **2005**,
473 35, 2203.
- 474 [45] M. Hobbins, Home-based drinking water purification through sunlight: from
475 effectiveness to health effectiveness. PhD dissertation University of Basel, **2004**.
- 476 [46] M.N.B. Momba, C.L. Obi, P. Thompson, Survey of disinfection efficiency of small
477 drinking water treatment plants: Challenges facing small water treatment plants in
478 South Africa. *Water SA* **2009**, 35 (4), 485.
- 479 [47] P.F. Schuler, M.M. Ghosh, P. Gopalan, Slow sand and diatomaceous earth filtration of
480 cysts and other particulates. *Water Res.* **1991**, 25 (8), 995.
- 481 [48] L.C. Campos, M.F.J. Su, N.J.D. Graham, S.R. Smith, Biomass development in slow sand
482 filters. *Water Res.* **2002**, 36 (18), 4543.
- 483 [49] G. Logsdon, R. Kohne, S. Abel, S. LaBlonde, Slow sand filtration for small water
484 systems. *J. Environ. Eng. Sci.* **2002**, 1 (5), 339.
- 485 [50] D.H. Manz, P. Eng, New Horizons for Slow Sand Filtration. In Proceedings of the
486 Eleventh Canadian National Conference and Second Policy Forum on Drinking Water
487 and the Biennial Conference of the Federal-Provincial-Territorial Committee on
488 Drinking Water, Promoting Public Health Through Safe Drinking Water, April 3 – 6,
489 **2004** Calgary, Alberta, pp 682–692.
- 490 [51] G., Palmateer, D. Manz, A. Jurkovic, R. McInnis, S. Unger, K.K. Kwan, B.J. Dutka,
491 Toxicant and parasite challenge of the Manz intermittent slow sand filter. *Environ.*
492 *Tox.* **1999**, 14 (2), 217.

- 493 [52] W. Duke, A. Mazumder, R. Nordin, D. Baker, The use and performance of Biosand
494 Filters in the Artibonite Valley of Haiti: A field study of 107 households. *Rural and*
495 *Remote Health* **2006**, 6:570 (<http://www.rrh.org.au>).
- 496 [53] M.A. Elliott, C.E. Stauber, F. Koksas, F.A. DiGiano, M.D. Sobsey, Reductions of E. coli,
497 echovirus type 12 and bacteriophages in an intermittently operated household-scale
498 slow sand filter. *Water Res.* **2008**, 42 (10-11), 2662.
- 499 [54] H. Chiew, M.L. Sampson, S. Huch, S. Ken, B.C. Bostick, Effect of groundwater iron and
500 phosphate on the efficacy of arsenic removal by iron-amended biosand filters.
501 *Environ. Sci. Technol.* **2009**, 43 (16), 6295.
- 502 [55] C. Noubactep, Besseres Trinkwasser an jeder Stelle in ländlichen Gebieten Afrikas.
503 *Afrika & Wissenschaft* **2008b** 1 (3), 36.
- 504 [56] C. Noubactep, P. Woafu, Elemental iron (Fe⁰) for better drinking water in rural areas of
505 developing countries. In Merkel B.J., Hasche-Berger A. (Eds.) *Uranium in the*
506 *Environment*. Springer, Berlin, Heidelberg; **2008**, pp. 121–130.
- 507 [57] E. Alemayehu, B. Lennartz, Virgin volcanic rocks: Kinetics and equilibrium studies for
508 the adsorption of cadmium from water. *J. Hazard. Mater.* **2009**, 169 (1-3), 395.
- 509 [58] H.M.N. Wright, K.V. Cashman, E.H. Gottesfeld, J.J. Roberts, Pore structure of volcanic
510 clasts: Measurements of permeability and electrical conductivity. *Earth Planet. Sci.*
511 *Lett.* **2009**, 280 (1-4), 93.
- 512 [59] M. Kitis, S.S. Kaplan, E. Karakaya, N.O. Yigit, G. Civelekoglu, Adsorption of natural
513 organic matter from waters by iron coated pumice. *Chemosphere* **2007**, 66 (1), 130.
- 514 [60] N. David, R. Heimann, D. Killick, M. Wayman, Between bloomery and blast furnace:
515 Mafa iron-smelting technology in North Cameroon. *African Archaeol. Rev.* **1989**, 7,
516 183–208.
- 517 [61] S.T. Childs, Style, technology, and iron smelting furnaces in Bantu-speaking Africa. *J.*
518 *Anthropol. Archaeol.* **1991**, 10 (4), 332.

- 519 [62] A. Verlinden, B. Dayot, A comparison between indigenous environmental knowledge
520 and a conventional vegetation analysis in north central Namibia. *J. Arid Environ.*
521 **2005**, 62 (1), 143.
- 522 [63] S. Chirikure, Metals in society: Iron production and its position in Iron Age communities
523 of southern Africa. *J. Social Arch.* **2007**, 7 (1), 72.
- 524 [64] A. Fuhrmann, Uran in Trinkwasser: Der Brunnen Barlissen wurde von Wasserverband
525 Leine-Süd bis auf Weiteres stillgelegt. *Göttinger Tageblatt*, 13 September **2008**.
- 526 [65] A.Y. Aleksanyan, A.N. Podobaev, I.I. Reformatskaya, Steady-state anodic dissolution of
527 iron in neutral and close-to-neutral media. *Protect. Met.* **2007**, 43 (1), 66.
- 528 [66] S. Nestic, Key issues related to modelling of internal corrosion of oil and gas pipelines –
529 A review. *Corros. Sci.* **2007**, 49, 4308.
- 530 [67] A.A. Attia, B.S. Girgis, N.A. Fathy, Removal of methylene blue by carbons derived from
531 peach stones by H₃PO₄ activation: Batch and column studies. *Dyes and Pigments*
532 **2008**, 76, 282.
- 533 [68] C. Noubactep, G. Meinrath, P. Dietrich, M. Sauter, B. Merkel, Testing the suitability of
534 zerovalent iron materials for reactive Walls. *Environ. Chem.* **2005**, 2 (1), 71.
- 535 [69] C. Noubactep, Characterizing the effects of shaking intensity on the kinetics of metallic
536 iron dissolution in EDTA. *J. Hazard. Mater.* **2009**, 170 (2-3), 1149.
- 537 [70] C. Noubactep, T. Licha, T.B. Scott, M. Fall, M. Sauter, Exploring the influence of
538 operational parameters on the reactivity of elemental iron materials. *J. Hazard. Mater.*
539 **2009**, doi: 10.1016/j.jhazmat.2009.07.097.
- 540 [71] R.J. Frankel, Design, construction and operation of a new filter approach for treatment of
541 surface waters in Southeast Asia. *J. Hydrol.* **1981**, 51 (1-4), 319.
- 542 [72] L. Cornejo, H. Lienqueo, M. Arenas, J. Acarapi, D. Contreras, J. Yáñez, H.D. Mansillac,
543 In field arsenic removal from natural water by zero-valent iron assisted by solar
544 radiation. *Environ. Pollut.* **2008**, 156 (3), 827.

545 [73] H. Tutu, T.S. McCarthy, E. Cukrowska, The chemical characteristics of acid mine
546 drainage with particular reference to sources, distribution and remediation: The
547 Witwatersrand Basin, South Africa as a case study. *Appl. Geochem.* **2008**, 23 (12),
548 3666.
549

549 **Table 1:** Some relevant water pathogens and related diseases. Compiled after ref. [21].

Microbes	Examples	Diseases
Bacteria	<i>Vibrio cholerae</i>	Cholera
	<i>Shigella sonnei</i>	Bloody diarrhea
	<i>Salmonella enterica</i>	Gastrointestinal illness
	<i>Helicobacter pylori</i>	Chronic ulcers and cancer
	<i>Escherichia coli</i>	Bloody diarrhea, kidney failure
	<i>Arcobacter butzleri</i>	Acute gastrointestinal illness
	Astro- and Caliciviruses	Gastrointestinal illness
Viruses	Hepatitis A/E virus	Acute liver disease (hepatitis)
	Rotavirus	Severe diarrhea
	<i>Blastocystis hominis</i>	Diarrhea and abdominal pain
Protozoa	<i>Entamoeba histolytica</i>	Gastrointestinal illness
	<i>Naegleria fowleri</i>	Amebic meningoencephalitis
	Fungi	<i>Aspergillus fumigatus</i>
<i>Fusarium solani</i>		Skin-related infections

550

551

551 **Table 2:** Some relevant characteristics of metallic iron and its main corrosion products. α is
 552 the molecular weight of iron to the molecular weight of the corrosion products. α_1 is
 553 the ratio of volume of expansive corrosion products to the volume of iron in the
 554 metallic structure. Compiled from refs. [38] and [39].

555

Name	Formula	Structure	Density (kg/m ³)	α	α_1
Iron	a-Fe	bcc	7800	-	-
Hematite	1/2 Fe ₂ O ₃	Trigonal	5260	0.699	2.12
Magnetite	1/3 Fe ₃ O ₄	Cubic	5180	0.724	2.08
Goethite	α -FeOOH	Orthorhombic	4260	0.629	2.91
Akageneite	β -FeOOH	Tetragonal	3560	0.629	3.48
Lepidocrite	γ -FeOOH	Orthorhombic	4090	0.629	3.03
	Fe(OH) ₂	Trigonal	3400	0.622	3.75
	Fe(OH) ₃	n.a.	n.a.	0.523	4.20
	Fe(OH) ₃ .3H ₂ O	n.a.	n.a.	0.347	6.40

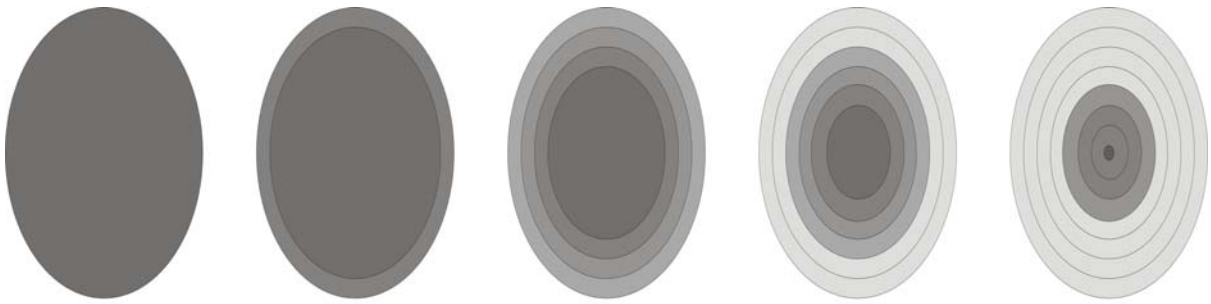
556 n.a. = not available

557

558

558 Figure 1

559



560

$t_0=0$

$t_1 > t_0$

$t_2 > t_1$

$t_3 > t_2$

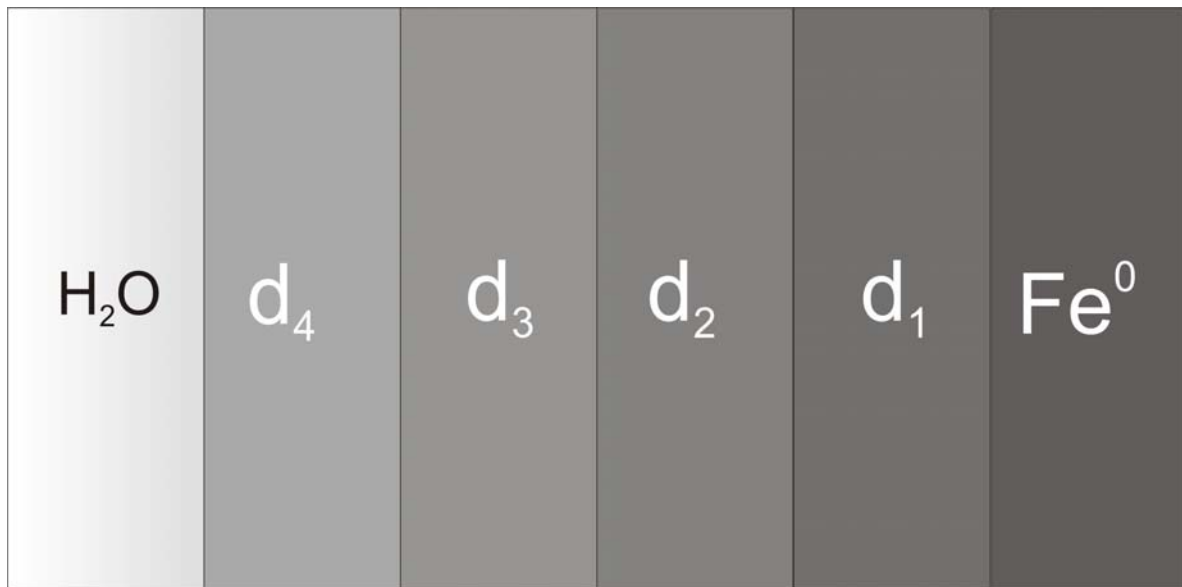
$t_4 > t_3$

561

562

562 Figure 2:

563

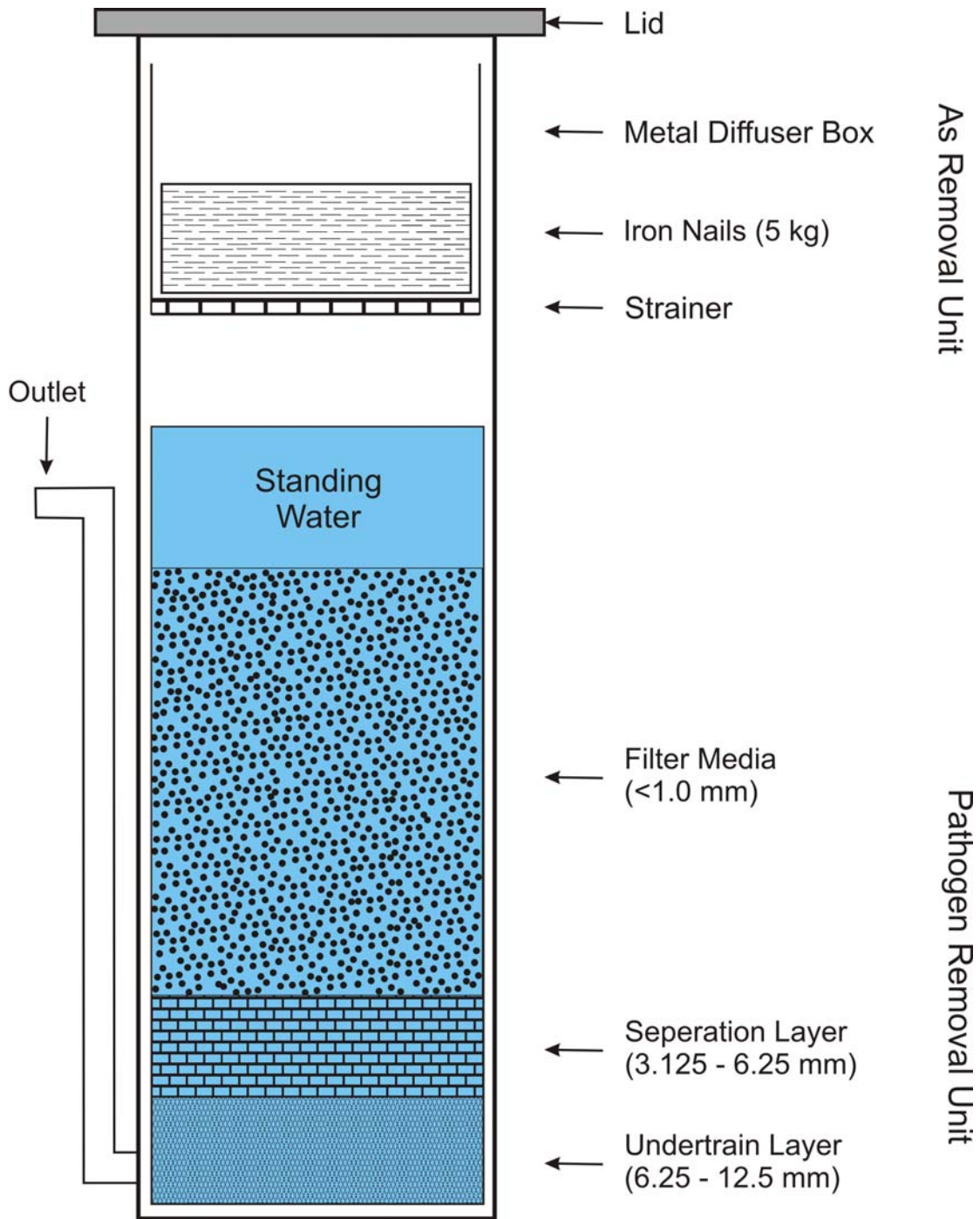


564

565

565 Figure 3

566



567

568

569

570

571

571 **Figure captions**

572

573 **Figure 1:** Time dependence evolution of Fe^0 and Fe corrosion products from a spherical
574 material assuming uniform corrosion. Fe^0 corrosion continuously produces
575 concentric layers of iron hydroxides which are transformed to iron oxides. It is
576 assumed (see text) that the three layers next to Fe^0 surface are reactive (d_1 , d_2 , d_3)
577 while the outer layers are non reactive (d_4).

578

579 **Figure 2:** Cross-sectional diagram of a uniformly corroding Fe^0 particle at $t > t_2$ (Fig. 1). d_1 ,
580 d_2 and d_3 are supposedly the reactive or transforming layers in which contaminants
581 may be adsorbed, co-precipitated or chemically transformed. d_4 is the growing
582 layer of aged corrosion products on which contaminants could adsorb. d_4 is less
583 porous than the inner layers but may be fissured.

584

585 **Figure 3:** Design of the filter tested for arsenic and pathogen removal in Cambodia by Chiew
586 et al. [54]. Rigorously the pathogen removal unit is a conventional BioSand filter
587 in which suspended solid are removed.