KANCHAN^{TM} ARSENIC FILTER: Can Iron and Arsenic Particles Migrate through the Sand Layer?

A research project submitted to

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And
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Submitted by
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Abstract

Sand samples were collected from two 12-months-old *Kanchan*^{TM} Arsenic Filters from Sunwal VDC of Nawalparasi District and from two 5-months-old *Kanchan*^{TM} Arsenic Filters from Dudrax VDC of Rupandehi District at 4 to 5 cm interval along the depth of sand layer for the determination of arsenic and iron concentrations and from one filter of each age group for the determination of the physical properties of sand, namely, grain size distribution, porosity and permeability. For all the four filters, the maximum iron and arsenic concentrations as well as arsenic to iron ratios in sand were found at the top depth, and low and approximately similar concentrations as well as ratios at the lower depths. The ANOVA analysis done between the iron and arsenic concentrations of the top depths and lower depths shows that there was a significant difference between concentrations. These results suggest that the physical properties of this particular sand was such that it did not allow arsenic absorbed on ferric hydroxide particles to significantly pass through the fine sand layer. The low and approximately similar concentrations at the lower depths was likely due to initial (i.e. background) concentrations of arsenic and iron. ANOVA analysis for the data tested from the four filters seemed to suggest that the iron and arsenic concentrations at various depths either are not time dependent or the profiles had reached steady state.

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List of Abbreviations

AAS: Atomic Absorption Spectrometer
ABF: Arsenic Bio-sand Filter
ANOVA: Analysis of Variance
ATU: Arsenic Treatment Unit
DWSS: Department of Water Supply and Sanitation
ENPHO: Environment and Public Health Organization
KAF: *Kanchan*^{TM} Arsenic Filter
MIT: Massachusetts Institute of Technology
NASC: National Arsenic Steering Committee
RWSSSP: Rural Water Supply and Sanitation Support Programme
SOA: State of Arsenic
VDC: Village Development Committee
WHO: World Health Organization

1. Introduction

The welfare and development of a society are dependent on a safe drinking water supply. Arsenic contamination of groundwater supply is not only a threat to human health in Nepal but also in many other regions in the world. Long term consumption of arsenic rich water can lead to chronic health problems, such as fatigue, hyper pigmentation, keratosis, skin cancer, cardiovascular and nervous affections, and cancer of the skin and internal organs[1, 2].

Although the ground water arsenic problem in Nepal is a relatively new issue, several organizations are actively involved in the study of this problem. The first Nepalese studies on arsenic in groundwater were carried out in 1999 by the Department of Water Supply and Sewerage, and the World Health Organization, and in 2000 by the Nepal Red Cross Society and the Japanese Red Cross Society. Both studies provided evidence of arsenic contamination in Terai region of southern Nepal[3]. The 1999 study by DWSS in the districts of Jhapa, Morang, and Sunsari in eastern Nepal found that 9% of the 268 tubewell water samples contained arsenic above the WHO guideline of 0.01 mg/L. The highest concentration was found to be 0.075 mg/L[4]. Nepal Red Cross Society initiated the Drinking Water Quality Improvement Program after a pilot study conducted in eight program districts in year 2000 found that 3% of the tube wells were found with arsenic above 0.05 mg/L [5]. The 2003 study by ENPHO showed that 3 % of the 1667 tube wells tested at different schools in 19 districts of Terai region were found above Nepal's interim guideline (0.05 mg/L of arsenic) and 16 % were above WHO guideline for arsenic in drinking water[6]. Another 2003 study by ENPHO in Kapilvastu, Rupandehi and Nawalparasi District found that 5.7% of the samples were found above Nepal standard of 0.05 mg/L of arsenic concentration and 8.1% samples exceeded the WHO standard of 0.01 mg/L of arsenic[7]. In the most seriously affected districts of Nawalparasi, Rupendehi, Kapilvastu, Bardiya, Kailali, Rautahat, Bara and Parsa, the arsenic concentration found in the tube well water can be 2 to 20 times greater than the Nepali Interim guideline of 0.05 mg/L or 10 to 100 times greater than the World Health Organization guideline of 0.01 mg/L[8].

The national database in 2003 consists of 18,635 arsenic-tested tube wells. Approximately 7.4% of all tube wells tested higher than the Nepal Interim Standard of 0.05 mg/L of arsenic concentration and 23.7% of tube wells in the Terai are above WHO Guideline[9]. The percentage of wells contaminated above 0.05 mg/L varies at district level from 0% in Dang, Chitwan, and Sunsari to 25.7% in Nawalparasi[10]. As per the 2004 database of 333,771 samples, 11.2% were found to be between 0.01 mg/L to 0.05 mg/L and 2.9% of the samples were found to be above 0.05 mg/L. The highest percentage of wells exceeding 0.05 mg/L was 14.77% in Nawalparasi, followed by 8.26% and 4.19% in Bara and Rupandehi respectively.

There have been a handful of efforts from MIT to study and develop appropriate household-level technologies for arsenic removal in Nepal. In 2001 Jessica Hurd studied the viability of three arsenic- removal technologies: Three-Gagri System, the Jerry Can System and the Arsenic Treatment Unit (ATU) made by Apyron Technologies, Inc. In 2002, Soon Kyu Hwang studied the Two-Kolshi system, Barika Poole studied arsenic removal through iron oxide coated sand and Tommy Ngai studied an activated alumina system, as well as conducted arsenic speciation tests in various wells in the Terai. Tommy Ngai of MIT in collaboration with Environment and Public Health Organization (ENPHO) and Rural Water Supply and Sanitation Support Programme (RWSSSP) went on to design an innovative arsenic removal technology: The Arsenic Biosand Filter (ABF), which won the MIT IDEAS Competition 2002 Lemelson International prize and the World Bank Development Market Place Global Competition 2003 award. The Arsenic Biosand Filter was later renamed as the *Kanchan*^{TM} Arsenic Filter (KAF).

Studies conducted so far have shown that the *Kanchan*^{TM} Arsenic Filter is effective in removing arsenic, iron as well as bacteria together[11]. Based on a 2003 pilot study by Ngai and Walewijk, the *Kanchan*^{TM} Arsenic Filter was found to be effective in removing arsenic (range = 87 to 96%, mean = 93%), total coliform (range = 0 to >99%, mean = 58%), *E. Coli* (range = 0 to >99%, mean = 64%), and iron (range = >90 to >97%, mean = >93%) [12]. The users liked the high flow rate (range = 4 to 23 L/hr, mean = 14 L/hr), simple operation, minimal maintenance, as well as the clean-looking and good-tasting water coming out of the filters[13]. They think the filter is a durable, permanent solution to their drinking water problems[14]. The results from 424 *Kanchan*^{TM} Arsenic Filter users surveys conducted in December 2004 to January 2005 showed that 93% of users found the appearance of KAF filtered water better, 95% found the taste of KAF filtered water better, 89% found smell of KAF filtered water better and 78% found considerable improvement in health[15]. As it is more technically, socially, economically and environmentally sound compared to two gagri and three gagri filters, this option can be more sustainable in the households[16]. From these studies it is obvious that is the arsenic problem is a serious threat in the Terai region and that the *Kanchan*^{TM} Arsenic Filter is one of the most viable options for arsenic mitigation in Nepal. Although this is the most widely used arsenic filter (>2,500 in the Terai Region), there was a need to further improve this filter to understand the precise mechanism of iron and arsenic removal in the sand layer.

2. Description of the ***Kanchan***^{TM} Arsenic Filter

2.1 Overview

Massachusetts Institute of Technology (MIT), in collaboration with ENPHO and RWSSSP has developed the *Kanchan*^{TM} Arsenic Filter, KAF (previously called the Arsenic Bio-sand Filter), a modified version of the conventional Bio-sand that was developed by Dr Manz of the University of Calgary. The Bio-sand Filter is based on the principle of slow sand filtration developed in the 1800s. The Bio-sand Filter had been introduced in the Terai region previously for removal of iron and bacteriological contamination. The modified Bio-sand Filter called *Kanchan*^{TM} Arsenic Filter removes arsenic as well as iron and bacterial contamination without using any chemicals.

2.2 ***Kanchan***^{TM} Arsenic Filter Design

The *Kanchan*^{TM} Arsenic Filter is comprised of two removal units: the arsenic removal unit and the pathogen removal unit. The arsenic removal unit is consisted of a plastic diffuser basin, iron nails and some brick chips. The pathogen removal unit is consisted of sand and gravel layers. Cross section of the *Kanchan*^{TM} Arsenic Filter is shown in figure 1.

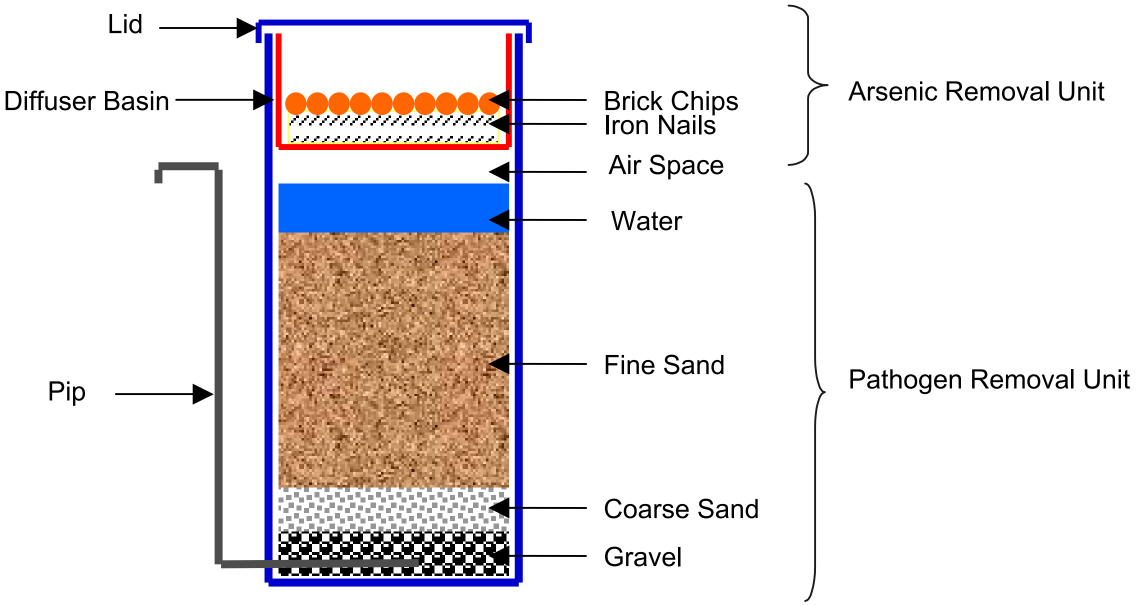


Figure 1: Cross section of the *Kanchan*^{TM} Arsenic Filter

2.3 Arsenic Removal

Many of the technologies for arsenic removal rely on few basic chemical processes. They are:

- Oxidation/Reduction
- Precipitation
- Adsorption.

In the adsorption process, arsenic is attracted to sorption sites on the surfaces of solid materials like iron hydroxide and aluminum hydroxide flocs. The *Kanchan*^{TM} Arsenic Filter uses rusted iron nails as an adsorption media.

In the *Kanchan*^{TM} Arsenic Filter, the iron nails are exposed to air and water, and rust quickly, producing ferric hydroxide particles. When arsenic contaminated water is poured into the filter, arsenic is quickly adsorbed onto the surface of the ferric hydroxide particles. Some of these arsenic-loaded ferric hydroxide particles flushed onto the underlying fine sand layer.

There are two possible hypotheses to the removal of these arsenic loaded ferric hydroxide particles by the sand layer. First, these arsenic loaded ferric hydroxide particles are trapped on top of the fine sand layer. This process is known as surface straining. Most of the arsenic is already adsorbed on to the ferric hydroxide, and almost all ferric hydroxide is trapped on the top of fine sand layer, as a result, arsenic is effectively removed from the water. Figure 2 below illustrates arsenic removal mechanism by surface straining.

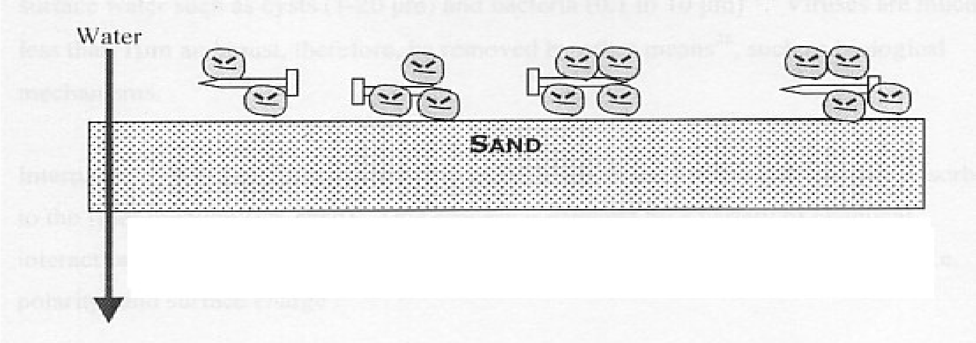


Figure 2: Faces represent arsenic, while the nails represent ferric hydroxide particles

According to the second hypothesis, iron instead of staying on the top of the sand layer enters inside the sand layer and mixes with the sand. This process is known as bed filtration. It was still not clear which one of these processes is taking place.

3. Rationale of the Study

Field research in 2004 by MIT and ENPHO showed that the arsenic removal of *Kanchan*^{TM} Arsenic Filter was in the range of 85-95%[17]. Independent field studies of the *Kanchan*^{TM} Arsenic Filter in Nepal by the Tribhuvan University, Kathmandu University and United States Peace Corp showed 87-95+% arsenic removal rate[18, 19]. It is believed that arsenic removal is due to the adsorption of arsenic on iron hydroxide particles. However there is a further need to understand this mechanism with relationship to the arsenic-to-iron-ratio, adsorption capacity, saturation, background values, and breakthrough in the sand layer of the *Kanchan*^{TM} Arsenic Filter and also to find out how deep the arsenic and iron particles can go through the sand layer in the *Kanchan*^{TM} Arsenic Filter. This will help to decide on the minimum height of the sand layer in the filter. Furthermore this research seeks to understand how the physical properties of sand can affect arsenic and iron removal.

4. Research Objectives

The broad objective of this study is to better understand the relationship between the physical properties of sand and iron and arsenic removal in the *Kanchan*^{TM} Arsenic Filter.

The specific objectives of this study are as follows

- To determine the iron particle concentration profile with respect to sand depth,
- To understand how the "age" of the filter, which is a representation for usage rate or volume of water treated, may affect the shape of the iron and arsenic profile ("Age" was defined in terms of date of installation, number of users, and frequency of use), and
- To identify and understand the physical properties of the fine sand and their influence on iron and arsenic removal.

5. Materials and Methods

5.1 Field Sampling

Sand samples were collected from four existing concrete filters at 4 to 5 cm interval along the depth of sand layer (till the full depth of the fine sand layer in the filter). Two "older" filters were selected from Sunwal VDC of Nawalparasi District, which had been installed in March 2004 (i.e. 12-months old). Two "newer" filters were selected from Dudrax VDC of Rupandehi District, which had been installed in October 2004 (i.e. 5-months old). The sand in each of the above filters was originally obtained from the same river source.

The diagram showing the sampling method is shown below in figure 3 below. While collecting the sand samples care was taken not to mix the sand and water of various depths. To ensure this, the excess water above the sand layer was scooped out with a spoon. A hole of about 5 cm diameter and 12-15 cm depth was made at any one corner of the sand layer. A spoon was used to scoop out the excess water, which drained into the hole. This ensures that the excess water from the top layers does not intermingle while taking the samples of the bottom layers. The depth of the sampling point, which was at the middle of the cross section of the sand layer, was noted from a fixed reference point using a measuring tape. The spoon was cleaned with iron and arsenic free water and the first sample was taken. After the first sample was taken, 4 to 5 cm depth of sand was scooped from the sides of the cross section of the sand layer so as to leave the middle of the sand undisturbed. The hole was made further deeper by about 4 cm and excess water was drained out. Using a spoon dipped in iron and arsenic free water 4 to 5 cm depth of sand was scooped out from the middle of the cross section by moving the spoon from the middle to sides. This ensures that sand from the sides as well as sand sticking on the inner walls of the filter does not mix with the sampling point at the center of the cross section of the sand layer. Again the height of the sampling point was noted from the fixed reference point and using a spoon rinsed in iron and arsenic free water another sample was taken. This process was repeated till the bottom of the sand layer.

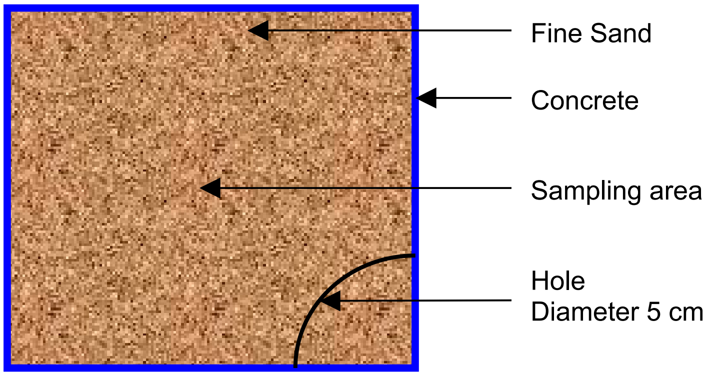


Figure 3: Top cross sectional view of the sand layer in the *Kanchan*^{TM} Arsenic Filter showing the sampling method

After collection of sand samples for testing of iron and arsenic content the sand from all four filters was removed and cleaned thoroughly by washing with water. Clean sand samples were collected from one of the filters from each age group for the determination of the physical parameters of sand. Two bottles of *Piyush* (a chlorine disinfection solution) were added to 10 L of clean water and poured into the filter before placing the sand, as prescribed in the usual filter installation procedure. The filters were reinstalled with the cleaned sand of about 38 cm depth and the standing water level above the sand layer of about 5 cm depth. Then, one of the filters from each age group was filled with water to the top (maximum water level). The flow rate of the filtered was measured based on the time (in seconds) needed to fill a 100 mL graduated cylinder. The collected sand samples were analyzed in the ENPHO laboratory for arsenic and iron content.

5.2 Laboratory Analysis

5.2.1 Iron and Arsenic Content

The sand was digested to extract iron and arsenic from the sand sample into a solution. The solution was analyzed in an Hydride Generation Atomic Absorption Spectrophotometer (HGAAS) for iron and arsenic concentration. At first, the iron and arsenic content was tested for the top five samples. The iron and arsenic profile was drawn for the top five samples. If the profile was stabilizing then there was no need to test the lower samples. If the profile was not stabilizing then the next 5 lower samples was tested. This process was continued till the profile becomes zero or till the lowest sample had been tested for iron and arsenic content.

Initially about 200g of soil was collected for each depth and mixed thoroughly. Then about 10g of the mixed sample for each depth was taken and the following step by step laboratory procedure was employed for iron and arsenic content determination in sand:

- Sample was dried at 105 degree Celsius to drive out moisture and cooled in desiccators
- Fixed weight (1-5 g) of sand was taken
- Digestion was done with 6N HCl and filtered for iron content determination and digestion was done with concentrated HNO_3 and H_2SO_4 till dense white fume developed for arsenic content determination
- A volume was made to 50 mL in a measuring flask
- The concentration of iron in the solution was determined by using Hydride Generation Atomic Absorption Spectrometer (HGAAS). Air acetylene flame technique was used for iron concentration determination and hydride generation technique for arsenic concentration determination.

- The result was reported on a dry basis in percentage (%) or on a dry basis in ppm

5.2.2 Porosity

The porosity of sand was determined by the beaker method. This method was based on replicating the field conditions in the laboratory. Dry sand was poured onto a beaker. Then water was poured onto the beaker to just cover or saturate the sand. This volume of water added (defined as Vv) and the total volume of the sand and water (defined as V) were noted. The following calculation was performed:

Porosity, **n = Vv * 100 / V**

5.2.3 Grain Size Distribution

Grain size analysis of sand was carried out by sieve analysis[20]. About 550 g of dry soil was taken and sieved through a selected set of sieves arranged according to their screen sizes, with the largest aperture sieve at the top and the smallest aperture at the bottom. A receiver was kept at the bottom and a lid was placed on the topmost sieve of the stack. The entire set of sieves was shaked for ten minutes.

Based on the total weight of sample taken and the weight of soil retained on each sieve, the percentage of the total weight of soil passing through each sieve (also termed as per cent finer than) was calculated as below:

Cumulative weight retained = sum of weight retained on all sieves of larger sizes and the weight retained on that particular sieve

Cumulative % retained on a particular sieve = (cumulative weight of soil retained on that sieve * 100)/ (total weight of soil taken)

Percentage finer than (or percent passing) the sieve under reference = 100 % - cumulative % retained

The result of a grain size analysis was represented in the form of a graph. The aggregate or cumulative weight, as a percentage of the total weight, of all grains smaller than any given diameter was plotted on the ordinate (y-axis) using an arithmetic scale; the size of the soil particles, in mm, was plotted on the abscissa (x-axis) using a logarithmic scale. In view of the very large range of particle sizes, a logarithmic scale becomes necessary.

The position, shape and slope of the curve indicate the type and graduation of the soil. In addition, certain grain diameters D, which correspond to a certain percent finer than on the grain-size distribution curve was determined.

Coefficient of uniformity Cu was defined as

$\mathbf{Cu = D_{60} / D_{10}}$

Coefficient of curvature Cc was defined as

$\mathbf{Cc = D_{30}^2 / (D_{10} * D_{60})}$

D_{60} = grain diameter corresponding to 60% finer than

D_{30} = grain diameter corresponding to 30% finer than

D_{10} = grain diameter corresponding to 10% finer than

For sand to be well graded Cc must lie between 1 and 3 and in addition to this Cu must be greater than 6.

5.2.4 Permeability

5.2.4.1 Darcy's Law

Permeability was determined by using Darcy's law[21]. The following formula was used:

Permeability (in cm/s), **k = Vmax * d / Hmax**

Vmax = maximum velocity or flow rate (cm/s)

d = depth of sand layer (cm)

Hmax = vertical distance between maximum water level and outlet (cm)

5.2.4.2 Allen Hazen Equation

Permeability was also determined by the empirical formula proposed by Allen Hazen[22]. For clean sands (with less than 5% fines) and D_{10} size between 0.1 and 3.0 mm:

Permeability (in cm/s), $\mathbf{k = CD_{10}^2}$

C = constant which varies from 0.4 to 1.2 with an average value of 1

D_{10} = grain diameter (in mm) corresponding to 10% finer than

5.2.4.3 Kozeny-Carman Equation

Permeability was also determined by the equation proposed by Kozeny-Carman[23].According to Kozeny-Carman equation the coefficient of permeability is defined as:

Permeability, $k = (1/ (C_s S_s^2 T^2))*(\gamma_w/\mu)*(e^3/ (1+e))$

C_s = shape factor (unitless)

T = tortuosity factor (unitless)

S_s = surface area per unit volume of soil solids (cm^{-1})

γ_w = unit weight of water ($g/cm^2/s^2$)

μ = absolute coefficient of viscosity (poise)

e = void ratio (unitless)

6. Results and Discussions

6.1 Iron Concentrations

6.1.1 Iron Results

Tables 1 to 4 show the depth of sand layers and their corresponding iron and arsenic concentration for the four filters. The ranges of iron concentration for filter 1, filter 2, filter 3 and filter 4 in percent were 0.56 to 1.81, 0.80 to 1.44, 0.71 to 1.13 and 0.75 to 1.03 respectively. Among the four filters, filter 1 had the maximum iron concentration of 1.81% at depth of 0 cm and filter 1 had the minimum iron concentration of 0.56% at depth of 13 cm.

Table 1: Depth of sand layer and corresponding iron and arsenic concentration for filter 1

	Parameters		Ratio of arsenic to iron concentrations
Depth (cm)	Iron concentration (%)	Arsenic concentration (ppm)	
0	1.81	6.10	3.37
5	0.90	0.75	0.83
10	1.01	0.60	0.59
13	0.56	0.14	0.25
17	1.11	0.22	0.20

Table 2: Depth of sand layer and corresponding iron and arsenic concentration for filter 2

Depth (cm)	Parameters		Ratio of arsenic to iron concentrations
	Iron concentration (%)	Arsenic concentration (ppm)	
0	1.44	2.10	1.46
4	0.94	0.37	0.39
8	0.80	0.45	0.56
13	0.91	0.39	0.43
18	0.94	0.52	0.55

Table 3: Depth of sand layer and corresponding iron and arsenic concentration for filter 3

Depth (cm)	Parameters		Ratio of arsenic to iron concentrations
	Iron concentration (%)	Arsenic concentration (ppm)	
0	1.13	4.00	3.54
4	0.90	2.37	2.63
8.5	0.71	0.52	0.73
12	0.79	0.55	0.70
16	0.80	0.35	0.44

Table 4: Depth of sand layer and corresponding iron and arsenic concentration for filter 4

Depth (cm)	Parameters		Ratio of arsenic to iron concentrations
	Iron concentration (%)	Arsenic concentration (ppm)	
0	1.03	2.90	2.82
4	0.80	0.44	0.55
8	0.87	0.29	0.33
12	0.80	0.40	0.50
16	0.75	0.28	0.37

Figure 4: Depth versus iron concentration (%) and arsenic concentration (ppm) for filter 1

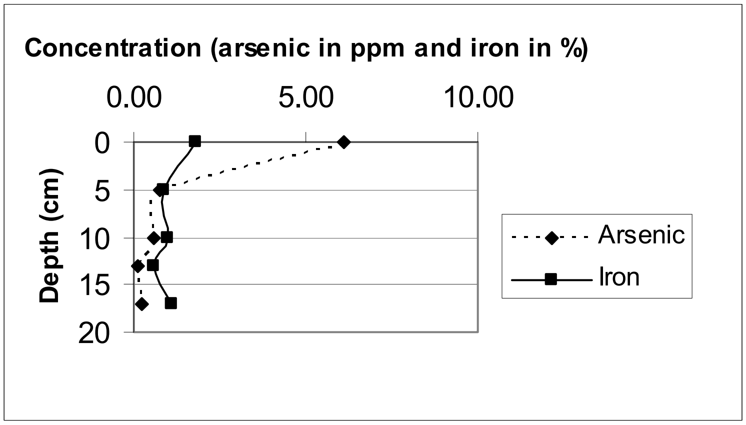


Figure 5: Depth versus iron concentration (%) and arsenic concentration (ppm) for filter 2

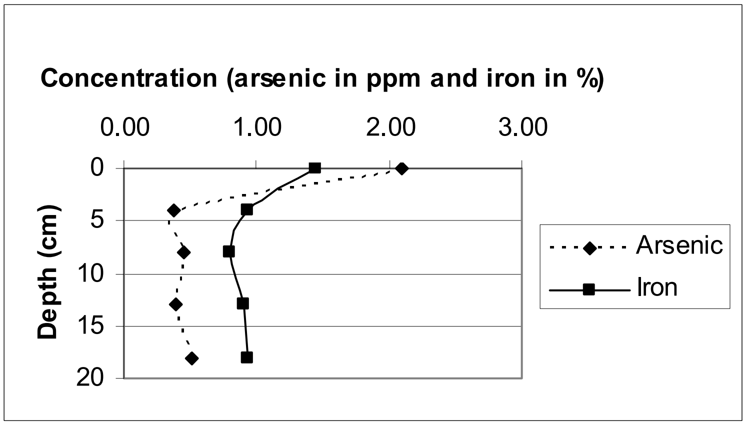


Figure 6: Depth versus iron concentration (%) and arsenic concentration (ppm) for filter 3

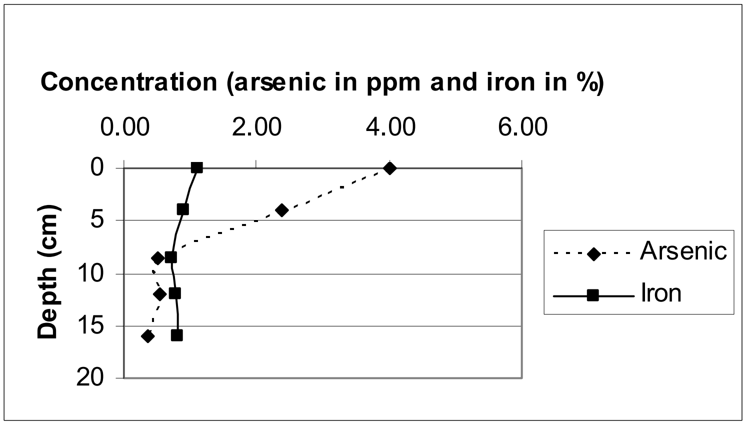
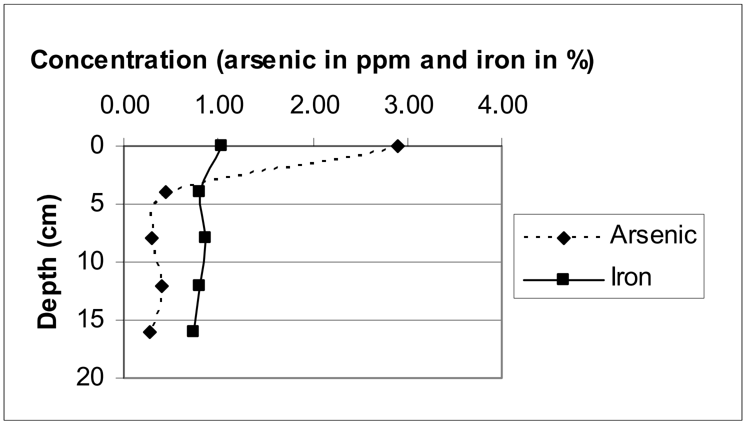


Figure 7: Depth versus iron concentration (%) and arsenic concentration (ppm) for filter 4



6.1.2 Discussion of Iron Results

For all the four filters the maximum iron concentration in sand layer was found at depth of 0 cm. This is probably due to the iron particles, which got trapped on the top of the fine sand layer, as they were unable to enter into the void spaces of the fine sand layer. At the bottom depths the graphs between the depth and iron concentration stabilized to approximately similar values with only slight fluctuations in concentrations (refer to Figure 4 to Figure 7). In general the iron concentration in soils varies widely, from 0.7% to 55%[24]. The minimum level of 0.7% iron concentration is approximately similar to the iron concentrations found in the lower depths in the sand layer. This suggests that the iron values in the lower samples could be contributed by the initial iron present in the natural sand (i.e. background values). These slight fluctuations may be due to possible sampling and laboratory errors, or due to natural background variation. So, it was determined unnecessary to test the bottom depths for iron concentration. For confirmation it is recommended that clean sand be installed and the initial iron concentration be measured. Then sampling could be done after some months.

Table 5 shows the ANOVA analysis done to determine whether iron concentrations were same for all filters. The ANOVA analysis showed no significant difference ($P > 0.05$). This may imply that the age of the filter had no significant correlation on the iron concentrations in sand. The data only showed that the iron profiles are similar for “newer” and “older” filters. The data only showed that the profiles either are not time dependent, or the profiles have reached steady state. However more filters should be tested to confirm the hypothesis. Furthermore, the ANOVA analysis also implies that the same age filters did not show any significant difference in iron concentrations in sand. This may suggest that there was no error in taking replications for filters of the same age.

Table 5: ANOVA F test value between 4 filters and iron concentrations

	Sum of squares	df	Mean square	F	P value
Between Groups	.183	3	.061	.784 ns	.520
Within Groups	1.243	16	.078		
Total	1.426	19			

df = degree of freedom, ns = non-significant at the 0.05 level of probability for the ANOVA F-test

Table 6 shows the ANOVA analysis done to determine whether iron concentrations of the top depth were significantly different from the iron concentrations of the bottom depths for the four filters. The ANOVA analysis showed that there was a significant difference in the top depth iron concentration values of the four filters in relation to the bottom depth iron concentration values. This seems to support the hypothesis that the iron hydroxide particles got trapped on the top of the sand layer.

Table 6: ANOVA F test value between iron concentration of top and bottom depths of 4 filters

	Sum of squares	df	Mean square	F	P value
Between Groups	.810	1	.810	23.663s	.000
Within Groups	.616	18	.034		
Total	1.426	19			

df = degree of freedom, s = significant at the 0.01 level of probability for the ANOVA F-test

6.1.3 Discussion of Errors

The sand samples were taken from the center, instead of taking representative samples from the whole cross section. So, it is possible that taking only samples from the center could create a bias. Care was also taken not to mix sand of various depths, but there could still be mixing.

From the samples taken in the field, only a small portion was used for laboratory analysis. Although the samples were mixed very well before samples were used for laboratory analysis, there could still be bias in taking the sample.

6.2 Arsenic Concentrations

6.2.1 Arsenic Results

The ranges of arsenic concentration (as shown in Table 1 to 4) in ppm for filter 1, filter 2, filters 3 and filter 4 were 0.14 to 6.10, 0.37 to 2.10, 0.35 to 4.00 and 0.28 to 2.90 respectively. Among the four filters, filter 1 had the maximum arsenic concentration of 6.10 ppm at depth of 0 cm and filter 1 had the minimum arsenic concentration of 0.14 ppm at depth of 13 cm.

6.2.2 Discussion of Arsenic Results

For all the four filters the maximum arsenic concentration in sand layer was found at depth of 0 cm. This shows that maximum arsenic got trapped at the uppermost depth. In general, it seems that the arsenic concentration decreased with increasing depth. The graphs between depth and arsenic concentration show a clear indication of this type of trend (Figure 4 to Figure 7). At the bottom depths the arsenic concentrations stabilized to approximately similar values with only slight variations. So, it is recommended not to test the bottom depths for arsenic concentration. The variations may be due to possible sampling and laboratory errors. The arsenic values in the samples could also be contributed by the initial arsenic present in the natural sand. For confirmation it is recommended that clean sand be installed and the initial arsenic concentration be measured. Then sampling could be done after some months.

The arsenic concentrations in the lower depths for each filter were not significantly different from each other. The concentration of arsenic in the lower depths may be due to the initial arsenic present in sand (i.e. background values). So, it is very important to get at least a crude estimate of the initial arsenic present in Dhumkibas sand. On the other hand, the top depth contained high arsenic concentrations. This is probably due to the arsenic particles, which got trapped on the top of the fine sand layer as they were unable to enter into the void spaces of the fine sand layer.

Table 7 shows the ANOVA analysis done to determine whether arsenic concentrations were same for all four filters. The ANOVA analysis showed no significant difference (P > 0.05). This may imply that the age of the filter had no significant correlation on the arsenic concentrations in sand. The data showed that the arsenic profiles are similar for "newer" and "older" filters. The data only showed that the profiles are either not time dependent, (the profiles have reached steady state), or the arsenic concentrations in the sand were background values. However more filters should be tested to confirm the hypothesis. Furthermore, the ANOVA analysis also implies that the same age filters did not show any significant difference in arsenic concentrations in sand. This may suggest that there was no error in taking replications for filters of the same age.

Table 7: ANOVA F test value between 4 filters and arsenic concentrations

	Sum of squares	df	Mean square	F	P value
Between Groups	2.806	3	.935	.343 ns	.795
Within Groups	43.626	16	2.727		
Total	46.431	19			

df = degree of freedom, ns = non-significant at the 0.05 level of probability for the ANOVA F-test

Table 8 shows the ANOVA analysis done to determine whether arsenic concentrations of the top depth were significantly different from the arsenic concentrations of the bottom depths for the four filters. The ANOVA analysis showed that there was a significant difference in the top depth arsenic concentration values of the four filters in relation to the bottom depth arsenic concentration values. This seems to support the hypothesis that the arsenic loaded iron hydroxide particles got trapped on the top of the sand layer.

Table 8: ANOVA F test value between arsenic concentration of top and bottom depths of 4 filters

	Sum of squares	df	Mean square	F	P value
Between Groups	33.489	1	33.489	46.574s	.000
Within Groups	12.943	18	.719		
Total	46.431	19			

df = degree of freedom, s = significant at the 0.01 level of probability for the ANOVA F-test

6.2.3 Discussion of Errors

The sand samples were taken from the center, instead of taking representative samples from the whole cross section. So, it was possible that taking only samples from the center could create a bias. Care was also taken so as not to mix sand of various depths, but there could still be mixing.

From the samples taken in the field, only a small portion was used for laboratory analysis. Although the samples were mixed very well before samples were used for laboratory analysis, there could still be bias in taking the sample.

6.3 Relation between Iron and Arsenic Concentrations

It can be seen from Tables 1 to 4 that the ratio of arsenic to iron is high in the upper layer and low and approximately similar for the lower layers for all the filters. The high ratio in the upper layer suggests that high amount of arsenic absorbed on ferric hydroxide particles may have got trapped in the upper layer without penetrating in the lower layers. The low and similar ratio in the lower layers was likely due to initial concentrations of arsenic and iron (i.e. background levels) because if arsenic absorbed on ferric hydroxides particles had entered into the lower layers the ratio would have been approximately similar to that of the upper layer. The difference in ratios may also imply that the sand in the upper layer had not reached its saturation values as the arsenic has not reached the lower layers.

6.4 Sand Physical Properties

Four filters were selected having sand from the same source. Sand parameters were determined for two filters, each belonging to a different age. The following parameters were analyzed to ensure that sand of the filters were similar.

6.4.1 Grain Size Distribution

Table 9 and Table 10 show the diameter of the sieves in millimeter and the corresponding weight retained in grams, cumulative weight retained in grams and the percent passing for filter 1 and filter 3 respectively. The diameter of the sieves ranged from 0.075 mm to 12.50 mm. For filter 1 and filter 3 the weight retained ranged from 0 g to 261.04 g and from 0 g to 246.23 g respectively. For both of these filters the maximum weight retained corresponds to a diameter of 0.425 mm. The cumulative weight retained ranged from 0g to 546.21 g and from 0g to 548.68 g for filter 1 and filter 3 respectively. For filter 1 and filter 3 the percent passing ranged from 0.69% to 100% and from 0.24% to 100% respectively.

Table 9: Grain size distribution analysis for filter 1

Diameter (mm)	**Weight retained (g)**	**Cumulative weight retained (g)**	**Percent passing (%)**
12.50	0.00	0.00	100.00
10.00	0.70	0.70	99.87
4.75	0.63	1.33	99.76
2.38	0.31	1.64	99.70
0.850	1.97	3.61	99.34
0.600	14.90	18.51	96.63
0.425	261.04	279.55	49.17
0.297	116.48	396.03	27.99
0.150	130.52	526.55	4.26
0.075	19.66	546.21	0.69

Table 10: Grain size distribution analysis for filter 3

Diameter (mm)	**Weight retained (g)**	**Cumulative weight retained (g)**	**Percent passing (%)**
12.50	0.00	0.00	100.00
10.00	0.00	0.00	100.00
4.75	0.00	0.00	100.00
2.38	0.81	0.81	99.85
0.850	1.52	2.33	99.58
0.600	14.20	16.53	96.99
0.425	246.23	262.76	52.23
0.297	125.66	388.42	29.38
0.150	146.51	534.93	2.74
0.075	13.75	548.68	0.24

From table 9 and table 10, it can be seen that the values of the parameters were approximately similar. This implies that the grain size distribution of both sands were similar. It can be seen from the tables that the upper half of the tables have low values of weight retained whereas the lower half of the tables have comparatively high values. This implies that most of the particles ranged from 0.6 mm to 0.075 mm diameter, that is, diameters found in the lower half of table. Even in the lower half of the tables, diameters ranging from 0.150mm to 0.425 mm correspond to a very high weight retained. The cumulative weight retained gives an indication of the weight retained on a sieve and all other sieves of larger diameter. The percent passing was high in the upper half of table compared to the lower half.

The grain size distribution curves of both the filters (Figure 8 for filter 1and Figure 9 for filter 3) were similar. This is a clear indication of the similar distribution of sand of the filters. The flatter or horizontal portions of the curves imply that the proportion of grain sizes between those diameters were relatively low. For example, for filter 1 the curve was horizontal from 0.850 mm to 12.50 mm, which means that the proportion of grain sizes between 0.850 mm to 12.50 mm was relatively low.

Figure 8: Grain size distribution curve for filter 1

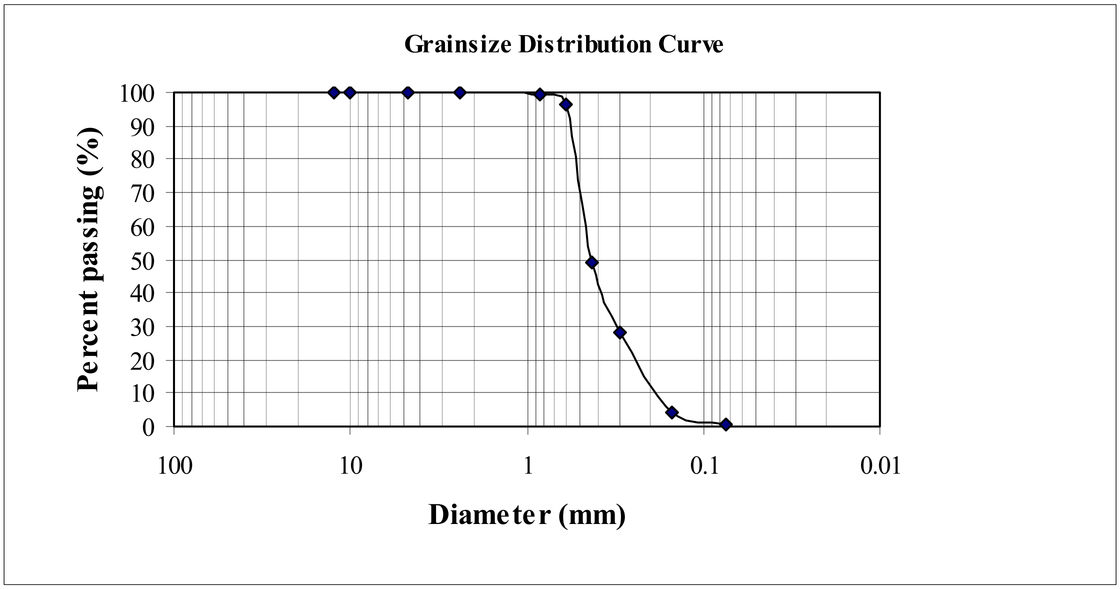


Figure 9: Grain size distribution curve for filter 3

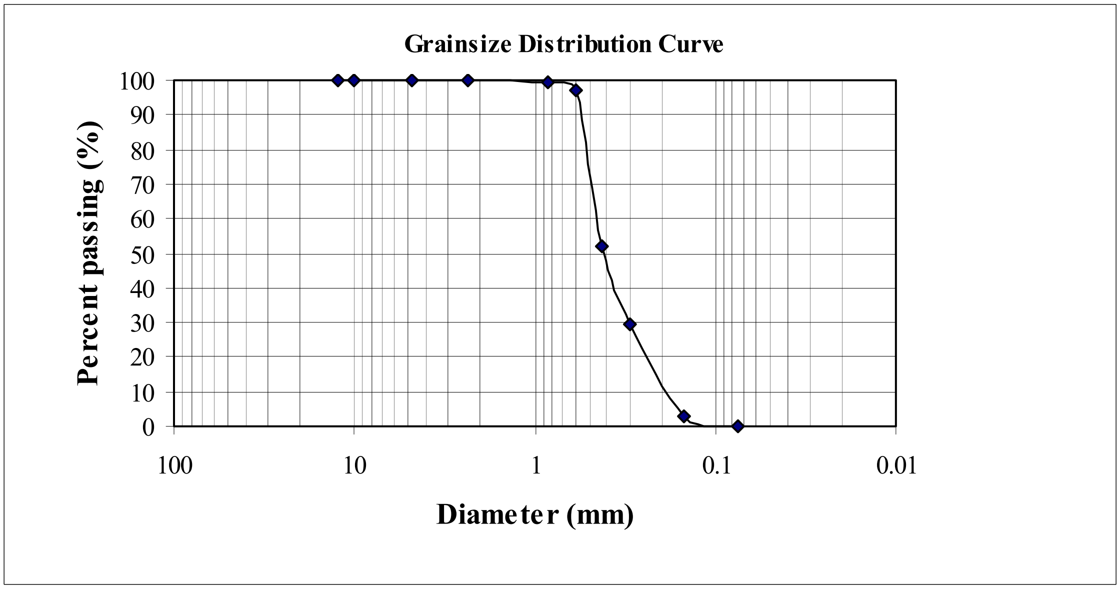


Table 11 shows the parameters determined from the grain size distribution curves. There was no gravel and coarse sand in the sand layers of both filters. However, it can be seen that the sand layer contains approximately the same percent of medium and fine sand. The values of the parameters for both the filters were also approximately equal. This was again a clear indication of the similar distribution of sand in both the filters. Since the values of Cu < 6 it signifies that the sand was poorly graded and of uniform graduation. The sand falls in this category because of the presence of only fine and medium sand types.

For the *Kanchan*^{TM} Arsenic Filter, the definition for fine sand is anything less than 1 mm, for coarse sand is 1-6 mm and for gravel is 6-15 mm. Table 11 has been computed on the basis of this definition.

Table 11: Parameters of grain size distribution curves of fine sand

Parameters	Filter 1	Filter 3
% of gravel (6 mm to 15 mm)	0.22	0
% of coarse sand (1mm – 6 mm)	0.4	0.39
% of fine sand (<1 mm)	99.38	99.61
Grain diameter corresponding to 10% finer than, D_{10} (mm)	0.19	0.19
Grain diameter corresponding to 30% finer than, D_{30} (mm)	0.31	0.3
Grain diameter corresponding to 60% finer than, D_{60} (mm)	0.46	0.46
Coefficient of uniformity, Cu	2.42	2.42
Coefficient of curvature, Cc	1.1	1.03

6.4.2 Porosity

The porosity of the sand sample of filter 1 and filter 3 was about 36% for both sand samples. This implies that out of 100 mL of sand, 36 mL for both filters was occupied by voids. In the case of the *Kanchan*^{TM} Arsenic Filter the sand was completely saturated with water, which means that out of 100 mL of sand, 36 mL for both filters was occupied by water.

6.4.3 Permeability

The permeability of both the samples determined by Allen Hazen formula was $3.61 * 10^{-2}$ cm/s. This implies that the velocity of flow under unit hydraulic gradient (that is, when depth of sand layer is equal to head loss) was $3.61*10^{-2}$ cm/s. According to Kozeny-Carman equation the permeability of both the samples was $2.22*10^{-2}$ cm/s. The permeability according to the flow measurement and Darcy's Law was $4.74*10^{-2}$ cm/s. It can be observed that the permeability values from all the methods were similar.

6.4.4 Relationship between Sand Physical Properties and Iron/Arsenic Profile

The iron and arsenic concentration results show that high amount of iron and arsenic gets trapped at the top depth of the fine sand layer. At the lower depths the iron and arsenic concentrations stabilized to low values compared to the values at the top depth. The low and approximately similar concentrations at the lower depths suggest that the initial iron and arsenic was contributing to these values. High amount of arsenic trapped at the top depth suggests that the values of the soil physical properties, namely, grain size distribution, porosity and permeability calculated above was such that it does not allow the iron and arsenic particles to enter into the fine sand layer. There may be a certain optimum value of the above sand physical properties, which do allow the entry of arsenic and iron particles into the fine sand layer. Usually a higher value of permeability and porosity may allow the entry of arsenic and iron particles. However, to determine such an optimum value more research is required where filters having sand of different physical properties are tested.

7. Conclusions

For all the four filters, the maximum iron and arsenic concentrations in sand was found at the top depth. High amount of iron and arsenic trapped at the top depth suggests that the values of the sand physical properties, namely, grain size distribution, porosity and permeability is such that it does not allow the iron and arsenic particles to enter into the fine sand layer. At the lower depths, the iron and arsenic concentrations seemed to stabilize to approximately similar values. The low and approximately similar concentrations at the lower depths suggest that the initial iron and arsenic was probably contributing to these values. The ANOVA analysis done between the iron and arsenic concentrations of the top depths and lower depths shows that there was a significant difference between concentrations. This again suggests that iron and arsenic got trapped at the top of the sand layer. Another approach to understanding the role of sand in iron and arsenic removal could be by the ratio of arsenic to iron. The high ratio of arsenic to iron in the upper layer suggests that high amount of arsenic absorbed on ferric hydroxide particles must have got trapped in the upper layer without penetrating in the lower layers. The low and similar ratio in the lower layers was likely due to initial concentrations of iron and arsenic (i.e. background levels) because if arsenic absorbed on ferric hydroxides particles had entered into the lower layers the ratio would have been approximately similar to that of the upper layers. The ANOVA analysis for the data tested from the four filters seemed to suggest that the iron and arsenic concentrations at various depths either are not time dependent or the profile had reached steady state.

8. Recommendations

It is recommended to:

- Find the value of the initial concentrations of arsenic and iron in Dhumkibas sand. This value can then be subtracted from the concentrations of arsenic and iron at various depths, to confirm the hypothesis that arsenic is trapped at the top sand layer,
- Determine the physical properties of more sand samples from different sources used in the *Kanchan*^{TM} Arsenic Filter, so as to get a comprehensive picture of the effect of sand physical properties on the arsenic and iron profiles,
- Set up several new filters and test for sand physical properties as well as initial arsenic and iron concentrations. Perform periodic sampling to get a detailed time series data of the iron and arsenic profiles as well as changes in sand physical properties, and
- Determination of the saturation capacity of sand (by using age as a proxy) in terms of iron and arsenic removal at the top of sand layer

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