Development of an Arsenic Mitigation Strategy for Bangladesh

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University of Oklahoma – May 4, 2006

Introduction

- 80 million people in Bangladesh are exposed to toxic levels of arsenic in well water
- The goal of this project was to develop an arsenic mitigation plan by designing an arsenic removal device that provides potable water

Introduction

- Four arsenic removal devices were considered:
  - **Activated Alumina** (designed)
  - Reverse Osmosis (designed)
  - Arsenic BioSand Filter (literature)
  - Iron Oxide Coated Sand (literature)

Introduction

- The community-sized activated alumina device was selected
  - Minimizes Cost
  - Maximizes sustainability and ease-of-use
- Each device serves one well
  - Approximately 250 people
- The cost is $4.79 per person, or $383 million for countrywide implementation over ten years

Arsenicosis

The various clinical manifestations caused by chronic arsenic toxicity due to prolonged drinking of arsenic-contaminated water, or chronic exposure to arsenic via other sources

The Arsenic Problem

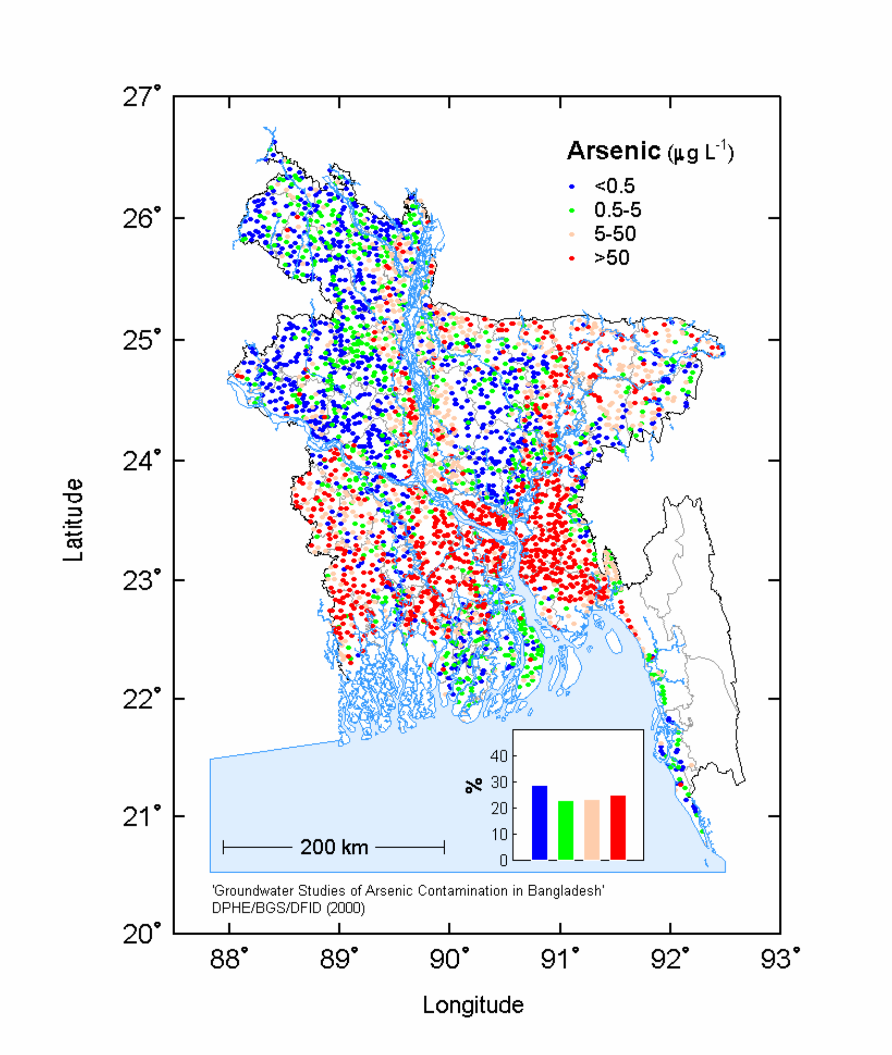
- Minor Health Effects
  - Hyper-pigmentation
    - Pigmentation alterations (hyper and hypo)
    - Melanosis
  - Hyper-keratosis
    - Thickening of the skin

The Arsenic Problem

- Major Health Effects
  - Bronchitis
  - Liver Damage
  - External and Internal Malignancies
    - Extreme skin lesions

The Arsenic Problem

- 30 Million at Extreme Risk
  - At risk of contamination levels > 50 ppb
- 50 Million at High Risk
  - At risk of contamination levels > 10 ppb

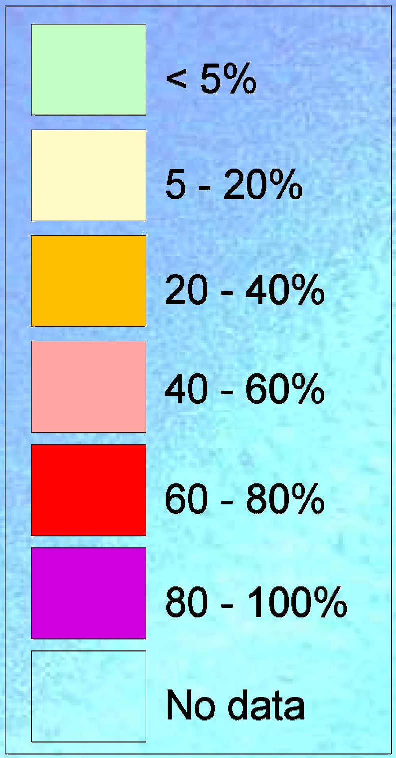


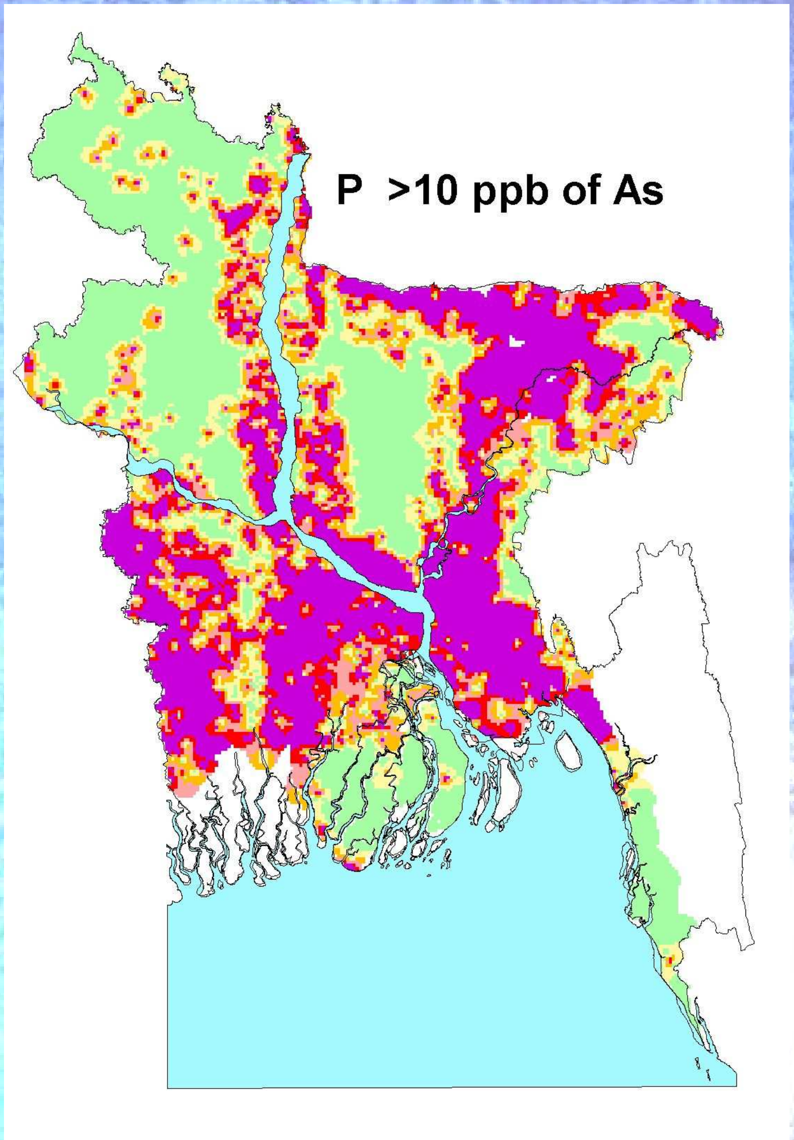
The Arsenic Problem

- Over 100 million drink well water
- Piped water only serves 10% of the population.
- Surface to ground water switch started in 60’s
- ***Until arsenic discovery in 1993, well water was regarded safe for drinking***
- Geological origin of arsenic contamination

The Arsenic Problem

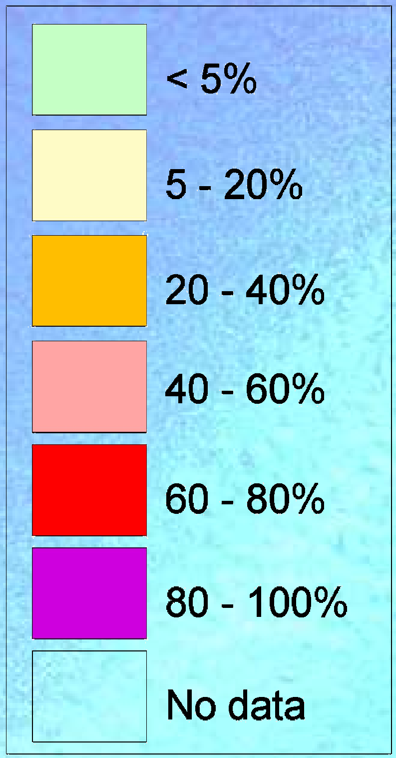
- Probability of locations exceeding various toxic thresholds

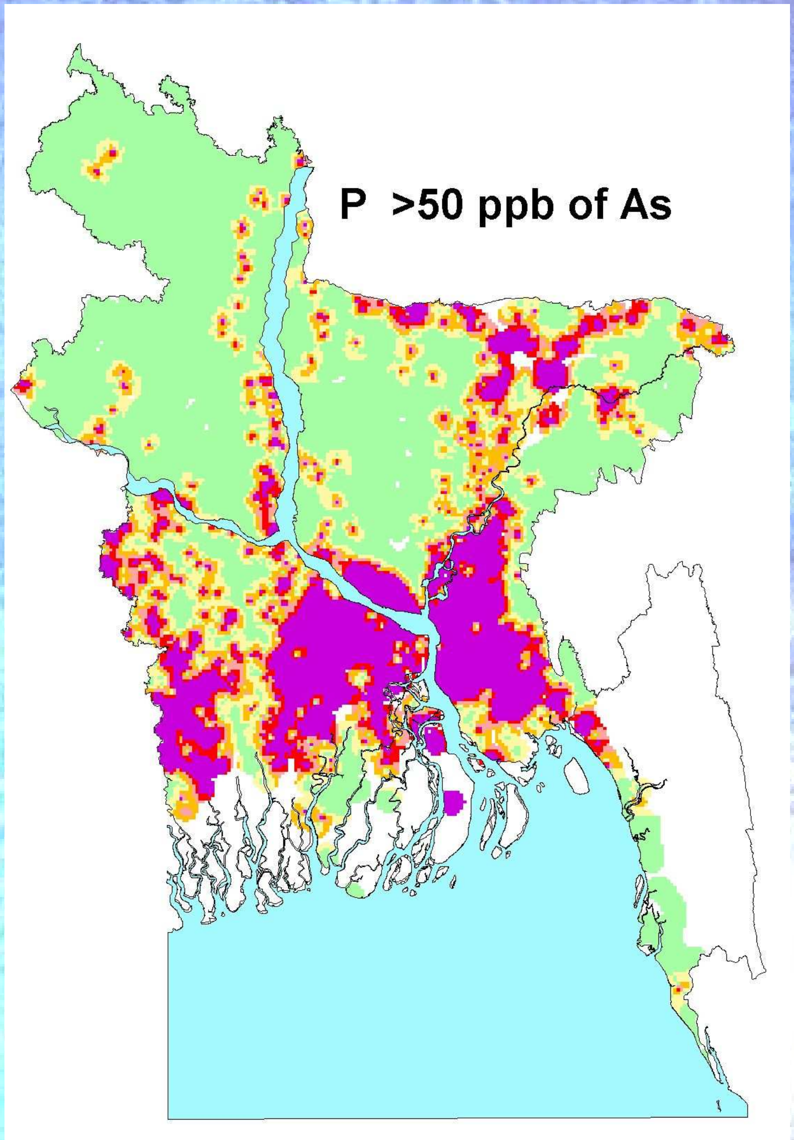




The Arsenic Problem

- Probability of locations exceeding various toxic thresholds





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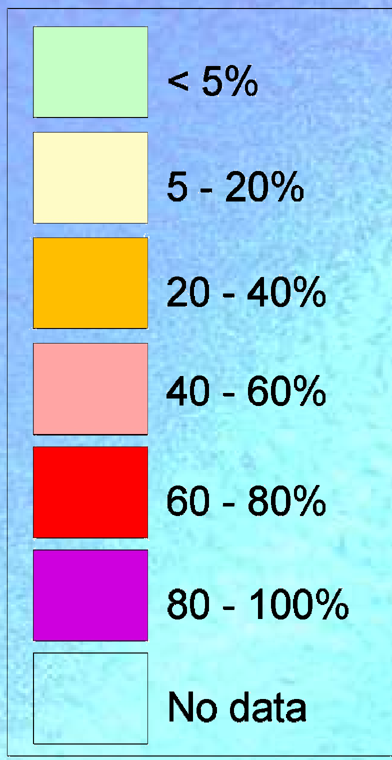

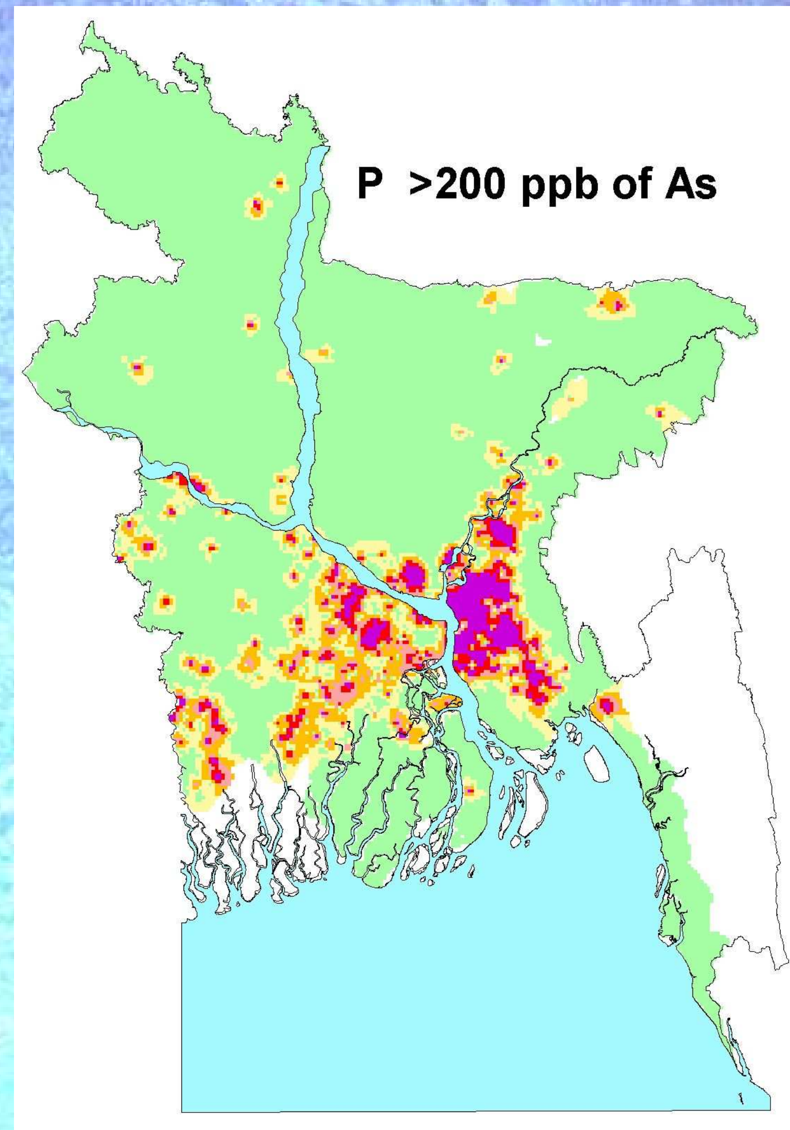

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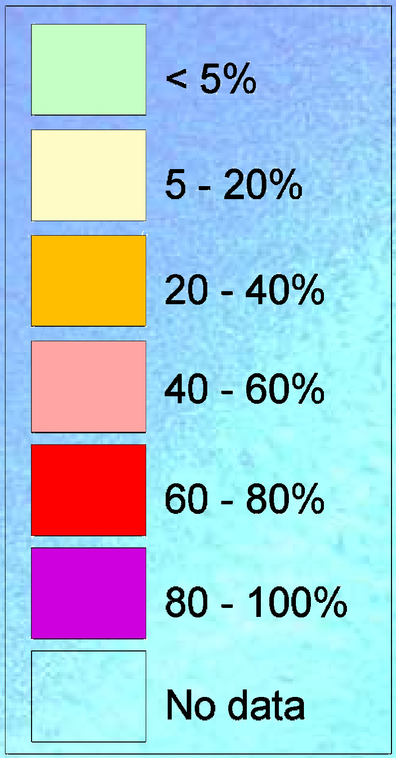
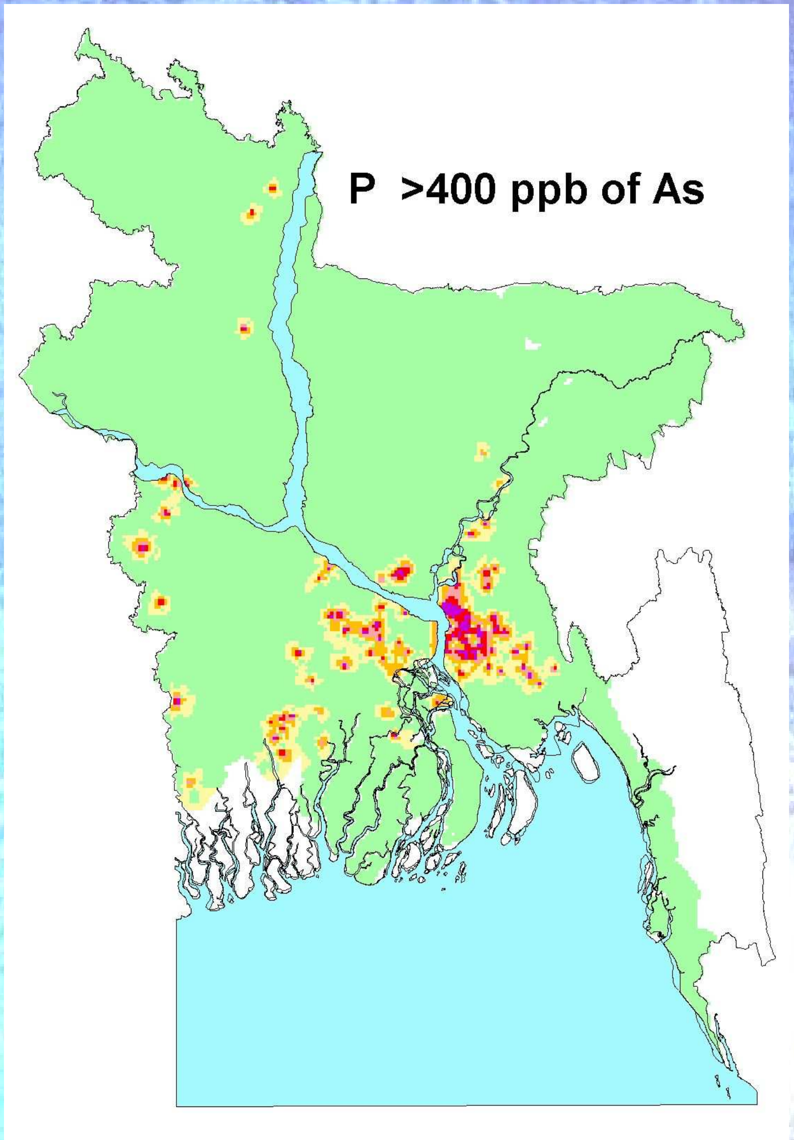
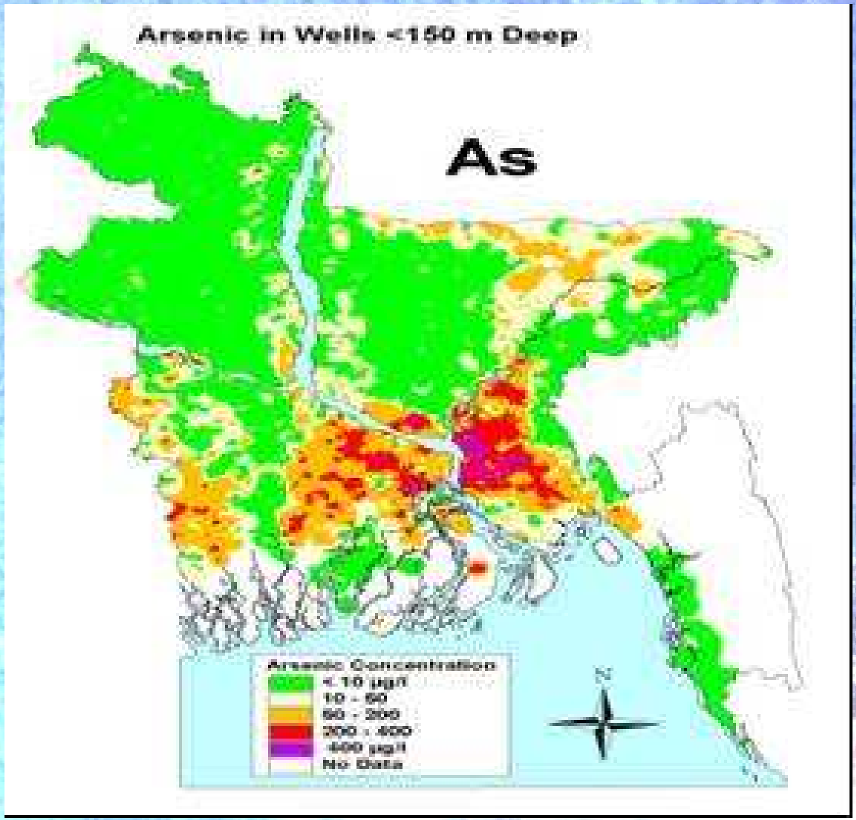




Water Quality: Arsenic

% of wells	Arsenic (ppb)
37	10-50
15.9	50 – 200
7.3	200 – 500
1.7	500 – 1000
0.1	> 1000



Water Quality

- Antimony, Cadmium, Chromium, Copper, Lead, Manganese, Molybdenum and Nickel levels all meet World Health Organization (WHO) standards
- 5% of wells have high boron levels
- High iron levels (1.1 mg/L)
  - No health risk, reduced by slow sand filter
- Low turbidity (few visible particles)

Slow Sand Filtration

- Each of the designs considered uses slow sand filtration to pre-filter the water to remove pathogens and larger particles

- A bio-film layer on top of the sand accomplishes the removal
  - Consists of algae, bacteria, and protozoa
  - Takes several weeks to “ripen”


C
B
D
E
http://www.slowsandfilter.com/biofilm.jpg
EHT=25.00 kV
WD= 5 mm
Detector= SE1
1µm
The Robert Gordon University, Aberdeen
FIGURE 3

Slow Sand Filtration

- Removal characteristics:
  - Turbidity (<1.0 NTU)
  - Pathogens (90-99%)
  - Heavy metals (Zn, Cu, Cd, Pb. 95-99%)
  - Arsenic (<47%)
  - Iron and manganese (>67%)

Slow Sand Filter Design

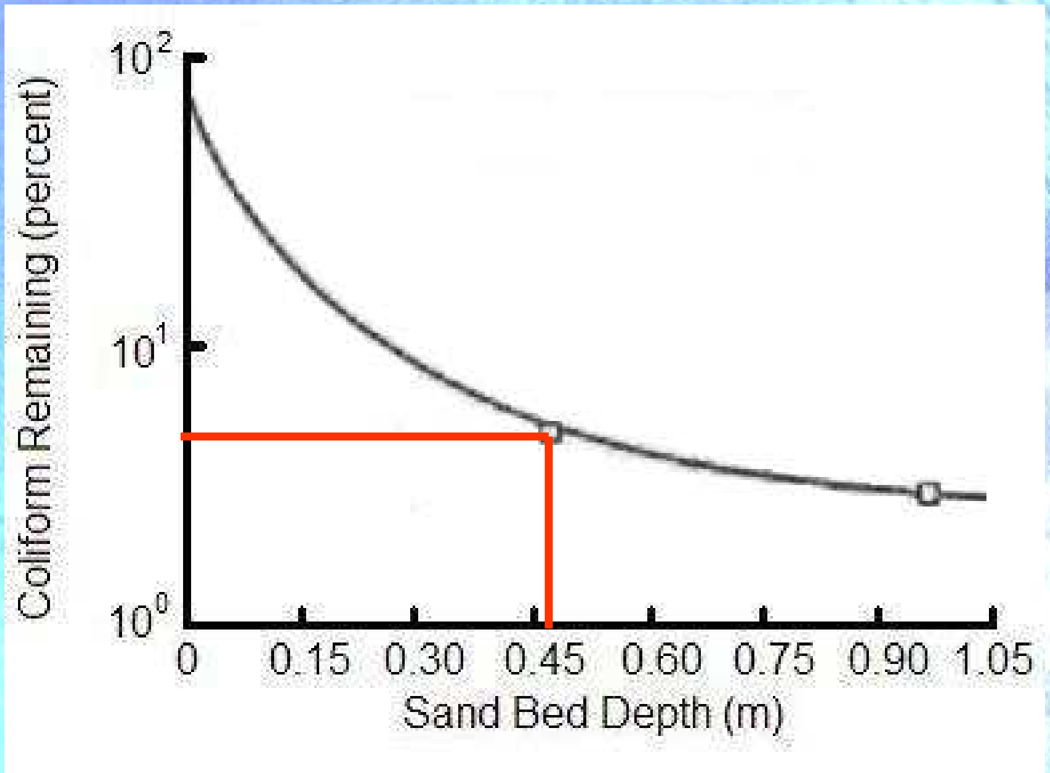
Dimensions
Height: 1.1 m
Diameter: 1.7 m

Slow Sand Filter Design

Variable	Optimized Value
Sand size (diameter)	0.35 mm
Tank diameter	170 cm
Sand bed depth	50 cm
Supernatant Water Height	35 cm
Maximum hydraulic loading	400 L/hour
Maintenance type	Wet harrowing

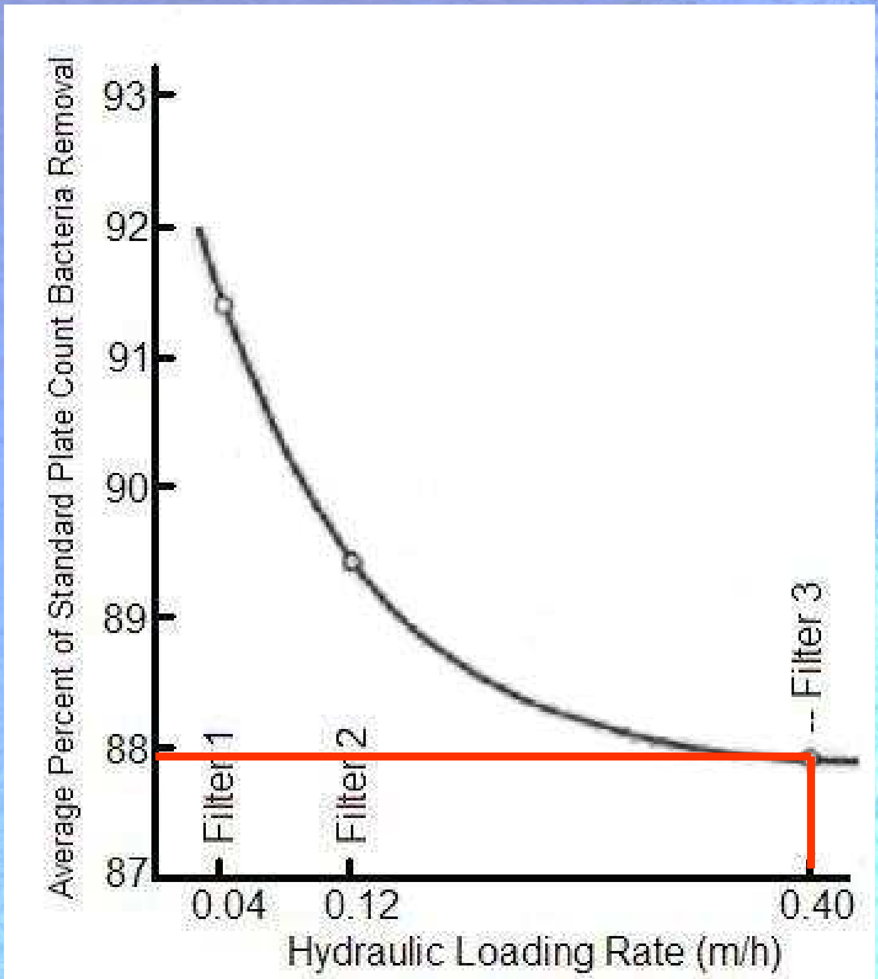
Slow Sand Filter Design

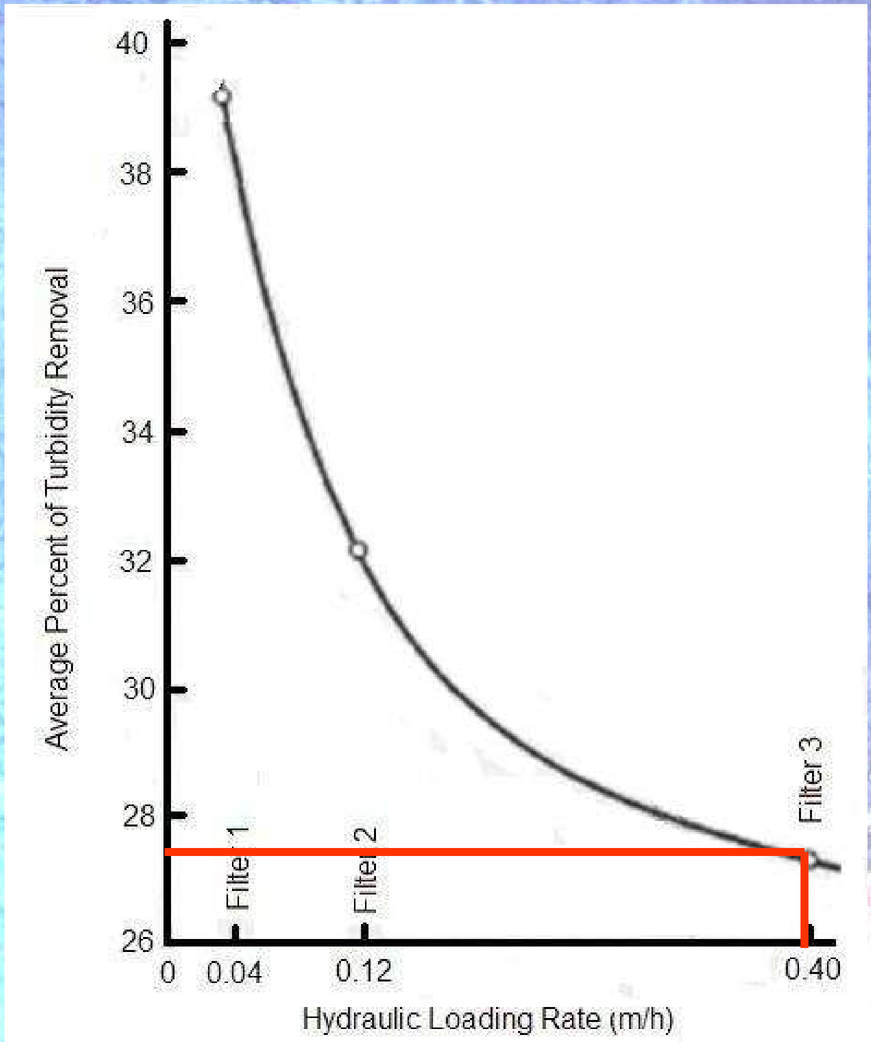
- Data from literature was used to determine the optimal sand filter properties



Bellamy, et. al. “Removing Giardia Cysts With Slow Sand Filtration.”

Slow Sand Filter Design





Bellamy, et. al. “Slow Sand Filtration: Influences of Selected Process Variables.”

Bellamy, et. al. “Removing Giardia Cysts With Slow Sand Filtration.”

Slow Sand Filter Maintenance

- As the bio-film layer increases, the flow rate through the filter decreases
- Maintenance is required when the flow rate decreases to an unacceptable level
  - Estimated every 6 months from literature and water quality data

Slow Sand Filter Maintenance

- Maintenance will be performed using the wet harrowing method
  1. The bio-film layer is agitated with a rake, suspending parts of the bio-film layer in the water
  2. The water is removed from the top
  3. Repeated until a significant amount of the bio-film is removed

Slow Sand Filter Construction

- Begin with large container
  - 170 cm diameter
- Shop construction
  - Placement of hole near bottom
- On-site construction
  - Sand depth:
    - 1 meter fine sand
    - 10 cm gravel
  - Standing water depth: 35 cm
  - 2 Polyester cloths to separate each layer
  - PVC Pipe attached and cemented

Removal Technologies

- Coagulation
  - Followed by microfiltration
  - Disadvantages:
    - User-addition of liquid coagulant
    - Stirring required, mixing times up to 60 minutes
- Ion Exchange
  - Effective for city-scale arsenic removal
  - Disadvantage: Expensive resins

Removal Technologies

- Adsorption
  - Iron oxide used in two comparison cases:
    - Iron oxide coated sand
    - Arsenic BioSand Filter (rusted nails)
  - Activated alumina
    - Selected for study
- Membrane Removal
  - Reverse osmosis selected for study

Reverse Osmosis Theory

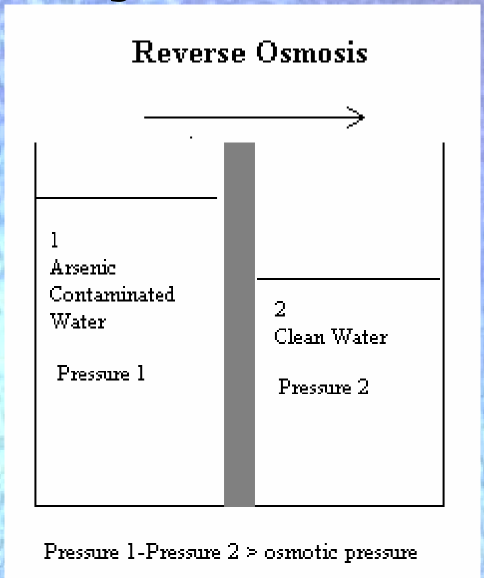
$$f_1^{salty} = f_1^{fresh}$$

$$\alpha_{water}^{(salty)} f_{water}^{o}\{T, P_{salty}\} = \alpha_{water}^{(fresh)} f_{water}^{o}\{T, P_{fresh}\}$$

$$\alpha_{water}^{(salty)} = x_{water}^{(salty)} \gamma_{water}^{(salty)} \qquad \alpha_{water}^{(fresh)} = 1$$

$$x_{water}^{(salty)} \gamma_{water}^{(salty)} f_{water}^{o}\{T, P_{salty}\} = f_{water}^{o}\{T, P_{fresh}\}$$

If $x_{water}^{salty}\gamma_{water}^{salty} < 1$, then $P_{salty} > P_{fresh}$



using the Poynting correction

$$f_{water}^{o}\{T, P_{fresh}\} = f_{water}^{o}\{T, P_{salty}\}\exp\left[\frac{v_1(P_{salty} - P_{fresh})}{RT}\right]$$

$$x_{water}^{salty} \gamma_{water}^{salty} f_{water}^{o}\{T, P_{salty}\} = f_{water}^{o}\{T, P_{salty}\}\exp\left[\frac{v_1(P_{salty} - P_{fresh})}{RT}\right]$$

Solving for $P_{salty} - P_{fresh}$, known as π

$$\pi = (P_\beta - P_\alpha) = -\frac{RT}{v_1}\ln(x_1^{\beta}\gamma_1^{\beta})$$

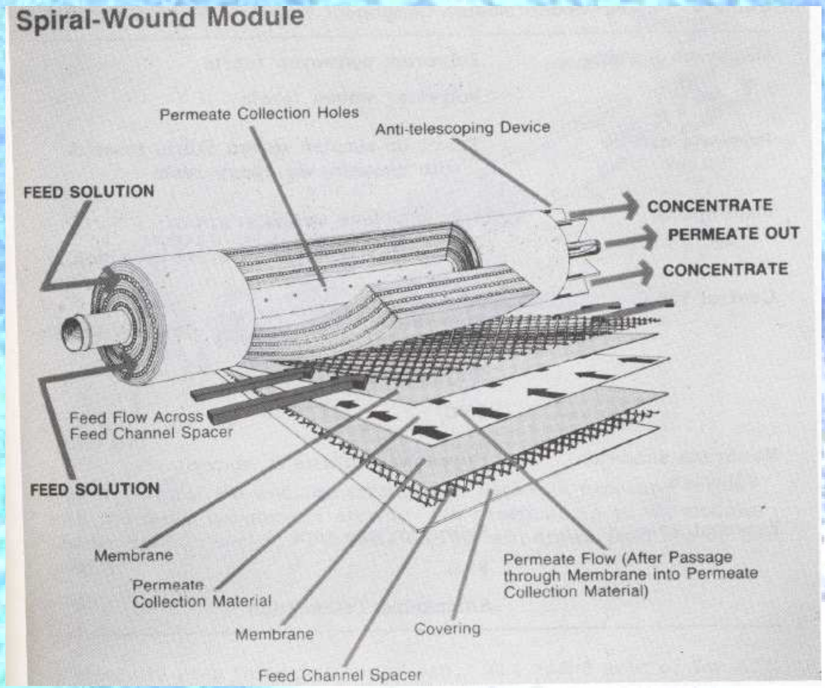
Reduces to

$$\pi = -\frac{RT}{v_1}(-x_2^{\beta}) = RTc_2$$

Reverse Osmosis Theory

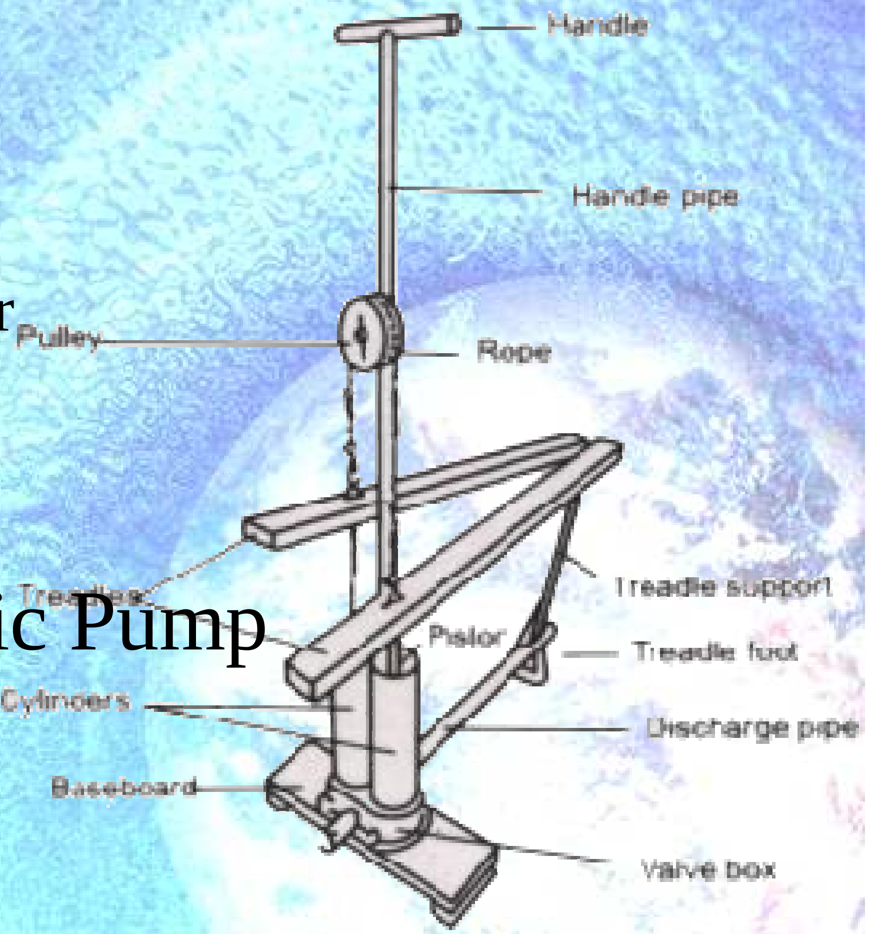
$$J_w = \frac{mass\ permeation\ rate}{membrane\ area}$$ (2-200 gal/ft2/day or "gfd")

- Rejection Rate
  - 3 gal rejected per one gal treated (http://wqa.org/)
- Types
  - *Spiral-wound*
  - Plate-and-frame
  - Tubular
  - Hollow-fiber modules
- Brine – *critical issue*



Reverse Osmosis

- Small Scale
  - Single home system most feasible due to pressure limitations
- Pre-Filter
  - Necessary pre-requisite
    - Satisfied by slow sand filter
- Hydraulics
  - The treadle pump
- Model MK1930 Hydraulic Pump
  - Used for cost estimation



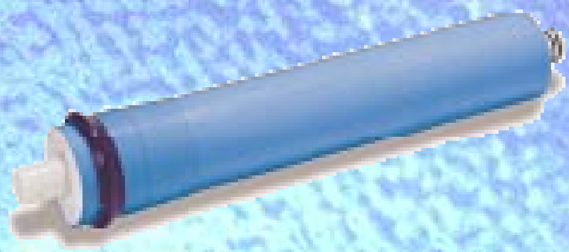
Reverse Osmosis

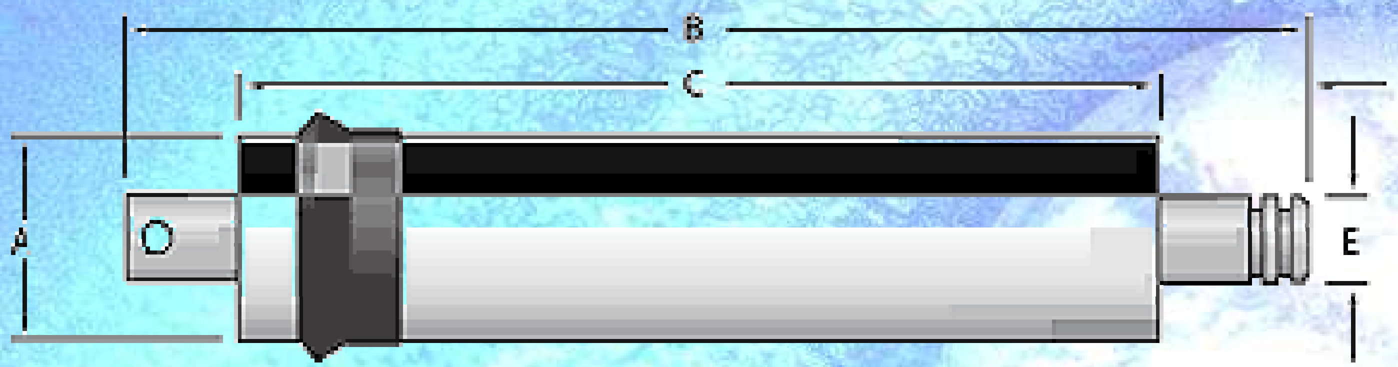
- RO System
  - Initial Installation – USRO 4-50 (50 gal/day)
  - $133

http://www.h2ofilter.net/cat.asp?i=75

Reverse Osmosis

- Membrane Replacement
  - TM-50
  - Life Span – 3 year





A: 1.80"	**B: 11.75"**	**C: 10.00"**	**D: 0.875"**	**E: 0.678"**

http://www.h2ofilter.net/product.asp?i=464

Reverse Osmosis Material Cost

	Cost	Specs
RO System	$133.00	
Storage Tank	$3.00	
Bucket	$3.00	Simple plastic
Pipe	$2.50	
Sand	$0.10	
Pump	$150.00	High Pressure Hand
Total	$290.00	

Total Initial Instillation w/ RO – $290

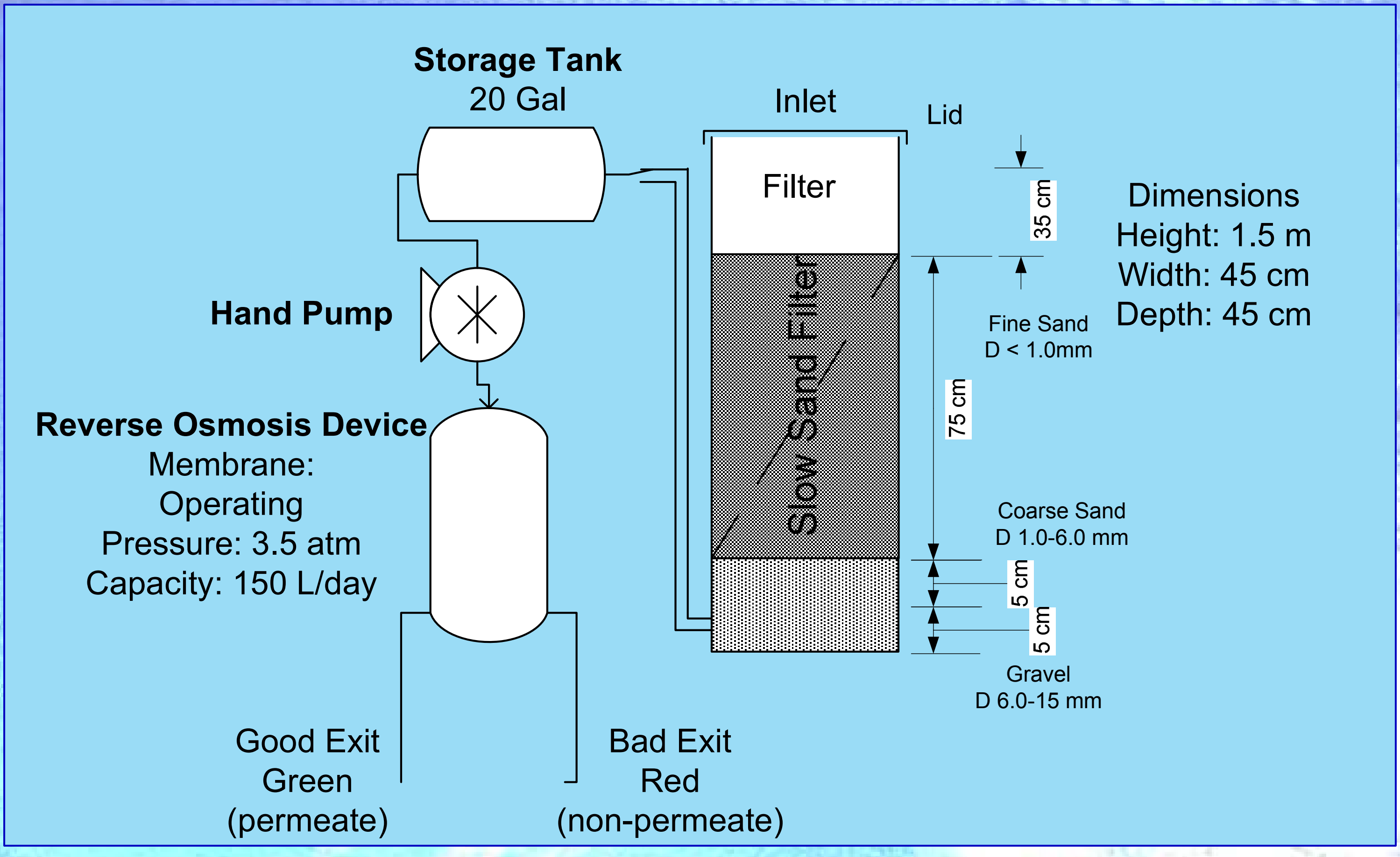
Reverse Osmosis Maintenance Cost

	Cost	Life Span	Yearly
Membrane	$ 39.00	3	$13.00
Storage Tank	$ 3.00	2	$1.50
Bucket	$ 3.00	3	$1.00
Pipe	$ 2.50	6	$0.42
Sand	$ 0.10	6	$0.02
Pump	$ 150.00	10	$15.00

Total Yearly for RO ***$32***

RO PFD

- Note: Two exit streams, one colored red, the other green



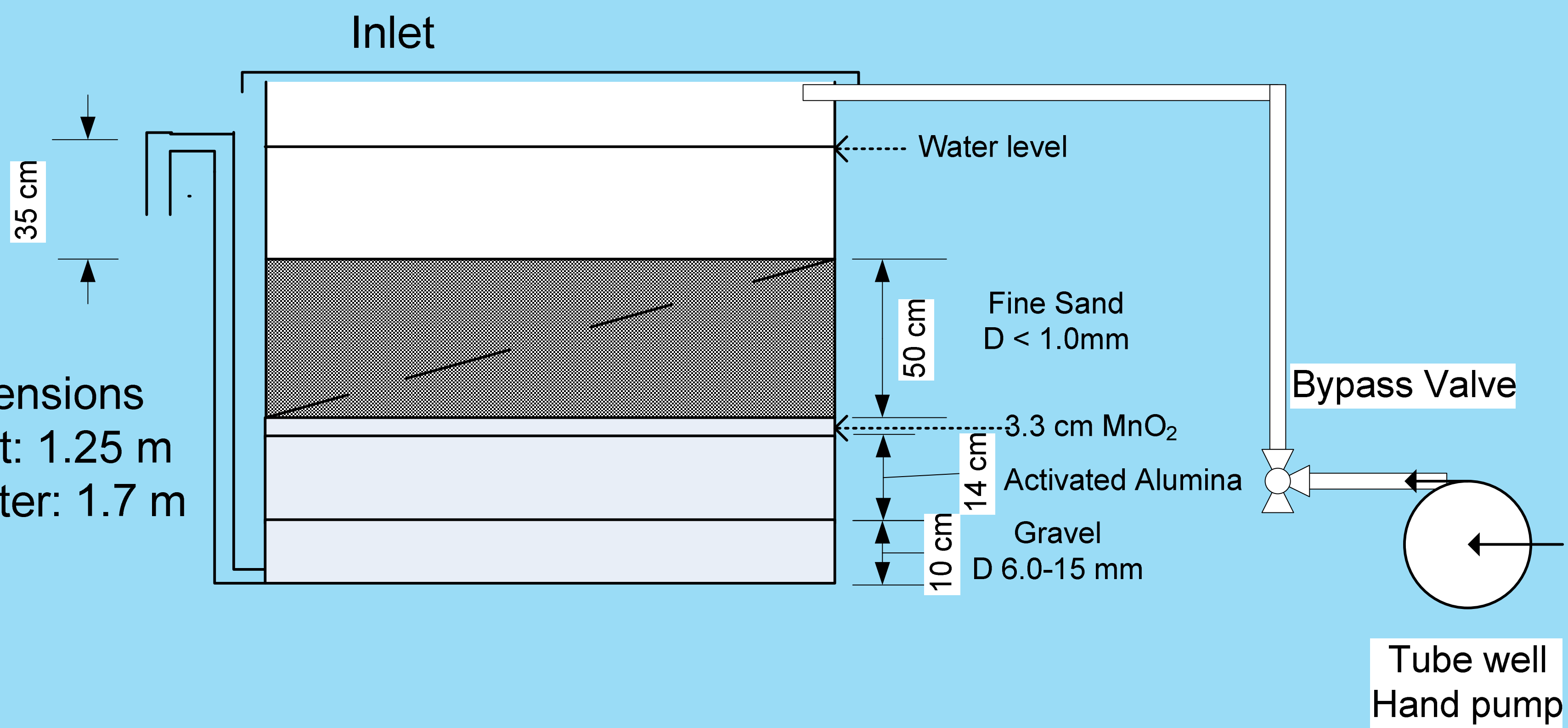
RO Manufacturing

- Identical to slow sand filtration manufacturing
- Only modification is addition of RO system
  - Water is first collected in a storage tank
  - Passes through pump to enter RO device

Activated Alumina

- Process Flow Diagram
- Chemistry:
  - Oxidation from arsenite [As(III)] to arsenate [As(V)]
  - Adsorption onto activated alumina
- Design and Cost:
  - Determination of optimal unit lifetime form initial and maintenance costs

Activated Alumina PFD



Dimensions
Height: 1.25 m
Diameter: 1.7 m

Oxidation

- Activated alumina adsorbs arsenate much more strongly than arsenite
- Manganese dioxide*
  - oxidizes 99.9% of arsenite to arsenate
  - empty bed contact time of 6 minutes
  - 1 ppm sulfur as a competing ion
  - Also adsorbs iron and manganese
    - ~67% of Fe and Mn are removed by sand

*Ghurye and Clifford. "As(III) Oxidation using chemical and solid-phase oxidants." American Water Works Association. Jan 2004, 96

Activated Alumina Chemistry

- Adsorption Selectivity
  - $OH^- > \boldsymbol{H_2AsO_4^-} > Si(OH)_3O^- > HSeO_3^-$
    $> \boldsymbol{F^-} > \boldsymbol{SO_4^{2-}} > CrO_4^{2-}$
    $>> HCO_3^- > Cl^- > NO_3^- > Br^- > I^-$
- Important competing ions:*
  - Sulfate at 1.0 mg/L
  - Fluoride at 0.2 mg/L

http://www.air-techengr.com

*Kinniburgh and Smedley, eds. "Arsenic Contamination of Groundwater in Bangladesh." *British Geological Survey Technical Report* WC/00/19, Volume 1

Activated Alumina Design

Physical Property	Size
Diameter (cm)	170
Standing Water Height (cm)	35
Fine Sand Depth (cm)	50
Gravel Depth (cm)	10
MnO_2 Depth (cm)	3.3
Activated Alumina Depth (cm)	14
Total Unit Height (cm)	112.3
Total Unit Height (ft)	3.7
Mass of MnO_2 (kg)	114
Mass of Activated Alumina (kg)	254

Activated Alumina Design

- Device cross-sectional area
  - Slow sand max hydraulic loading rate
  - Typical hand pump flow rate

$$A = \frac{\frac{15L}{\min} * \frac{60\min}{hr}}{400\frac{L}{m^2 hr}} = 2.25m^2$$

  - Corresponds to a 1.7 m diameter

AA: Manganese Dioxide Layer

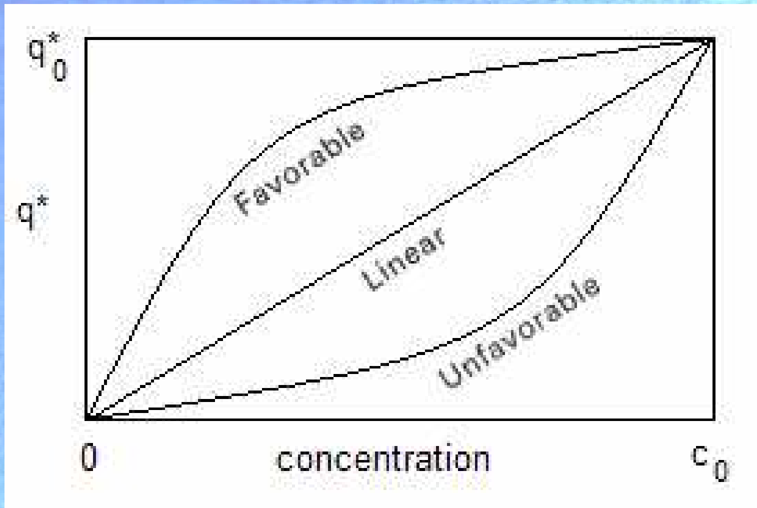
- The thickness of the manganese dioxide layer was determined by considering the empty-bed contact time requirement of six minutes

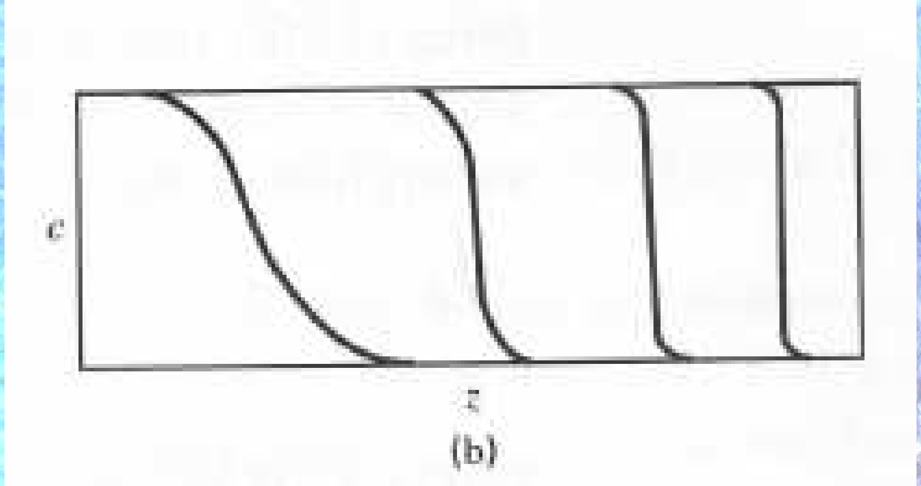
$$\text{EBCT} = \frac{\text{Height} * (\text{Cross-sectional Area})}{\text{Volumetric flow rate}}$$

- 3.3 centimeters

Activated Alumina Design

- Arsenate has a favorable adsorption isotherm for activated alumina, leading to a self-sharpening adsorption wavefront





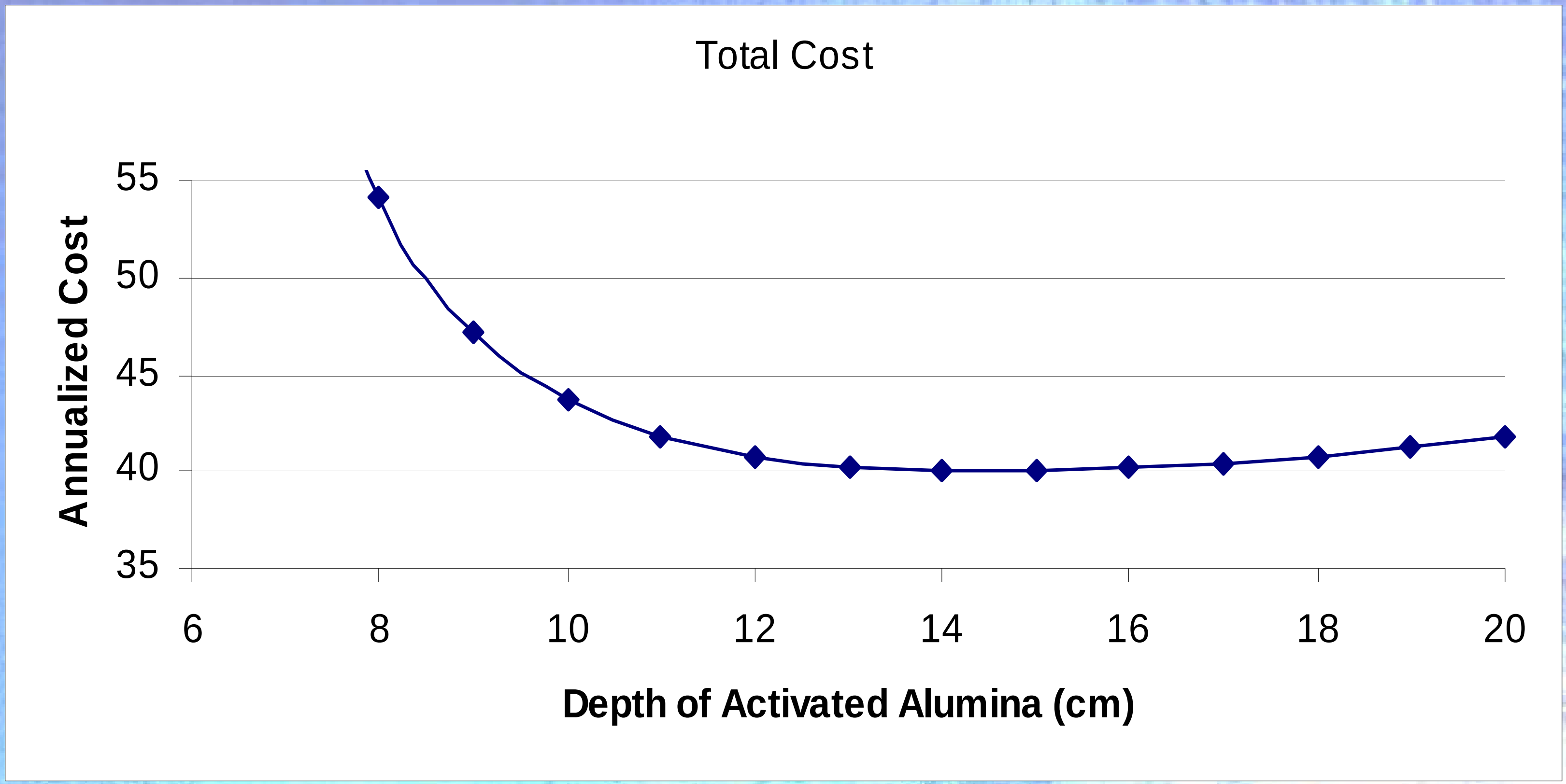
Seader, J.D. *Separation Process Principles*.
(Hoboken: John Wiley & Sons, Inc.,1998). p.835

Activated Alumina Design

- The required contact time for activated alumina is 12 minutes.*
  - Minimum thickness: 6.6 cm
  - Optimal thickness: 14 cm (21 min contact time)
- An annual cost was determined by using straight line depreciation for the activated alumina, and adding the annual maintenance cost for each thickness.

*Wang, et. al. "Arsenic Removal from Drinking Water by Ion Exchange and Activated Alumina Plants."

Activated Alumina Design



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Activated Alumina: Regeneration

- At pH's above 9.2, the surface of activated alumina becomes negative
- The negative surface repels the negatively charged arsenate ions
- A strong basic solution, such as potassium hydroxide or sodium hydroxide, can be used to regenerate the activated alumina

Activated Alumina: Regeneration

- During regeneration, studies show that approximately 5% of the activated alumina becomes deactivated
- Probable causes:
  - OH^- molecules adsorb as the basic solution is purged with well water and the pH drops below 9.2
  - Minor contributions from fouling or physical degradation of the alumina beads

Activated Alumina: Costs

Manufacturing Costs	
AA ($3.125 / kg)	$793.75
MnO_2 ($0.525/kg)	$59.85
Sand	$1.77
Tank	$250.00
Polyester Cloth	$5.00
Labor	$10.00
Piping	$20.00
Total	**$1,140.37**

Activated Alumina: Manufacturing

- Identical to slow sand filter construction
- Additional layers of manganese dioxide and activated alumina placed between the fine sand and the gravel

Comparison

Advantages

AA – Cheap, Simple

RO – Simple Operation

IOCS – One Step Process

ABF – User Friendly

Disadvantages

AA – Large OD- 5.6 ft

RO – Rejected water; Requires pressure

IOCS – IOCS; Manufacturing is complicated

ABF – Unconventional; Unproven

Comparison

Cost	Install	Maintenance
AA	$1140	$29.33
RO	$290	$31
IOCS	N/A	N/A
ABF	$40	N/A

Cost/Person/Yr	Install	Maintenance
AA	$4.79	$0.12
RO	$29	$3.10
IOCS	N/A	N/A
ABF	$4.00	N/A

Comparison

<u>Arsenic Removal</u>

AA – Sufficient

RO – Sufficient

IOCS – Sufficient

ABF – Sufficient

<u>Design</u>

AA – 2 Additional Steps: Oxidation & AA

RO – Additional RO system

IOCS – Substitute IOCS for fine sand

ABF – Additional Layer of Nails

Comparison

Lifetime

AA – 20 years for AA & MnO_2

RO – replacement3 years membrane replacement

IOCS – Replace/regenerate

ABF – N/A

Maintenance

AA – Regenerate AA yearly

RO – Membrane lasts 3 years

IOCS – Must Replace Sand

ABF – Must Replace Nails

Comparison

<u>Manufacture</u>
AA – Very similar to slow sand
RO – Addition of RO unit
IOCS – Complicated IOCS manufacture
ABF – Addition of nail container

<u>Credibility</u>
AA – Technically sound
RO – Trusted – Manufacturer
IOCS – OU Master Thesis Env. Engr.
ABF – MIT MBA Report

WINNER IS…ACTIVATED ALUMINA!!

Pilot Testing

- Pilot testing will verify device performance, and identify areas of improvement in the design
- Recommended Location:
  - Gazipur Union (county-size area)
  - 1000 households
  - 300-500 ppb arsenic contamination
  - Low literacy

Large-Scale Implementation

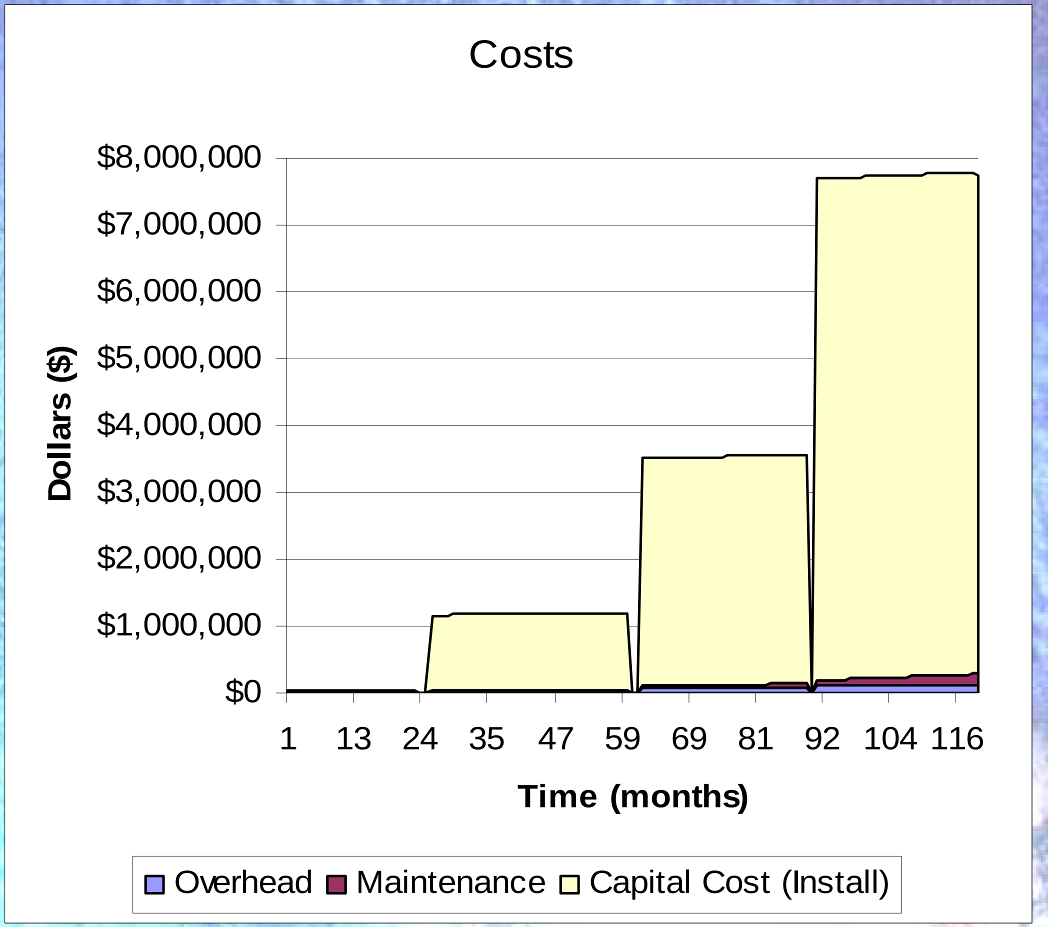
- Large-scale implementation
  - **Stage 1**: mitigate arsenic levels over 50 ppb
    - 30 million people at risk
    - Cost: $150 million
  - **Stage 2**: mitigate arsenic levels between 10-50 ppb
    - 50 million people at risk
    - Cost: $233 million

Economic Plan

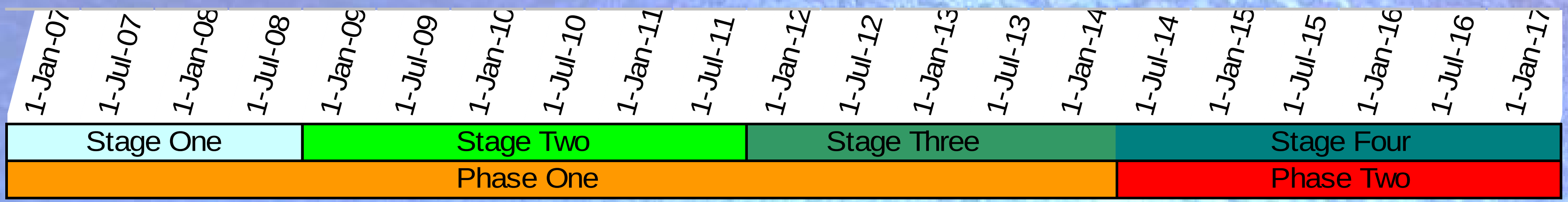
- Acquisition of Property
  - Rent for 1300 Sq. ft in Dhaka
    - $270 per month (www.velki.com/market)
  - Cost of Business Startup in Dhaka, Bangladesh
    - $370 - World Bank Economic Analysis
  - Labor
    - $6 per unit in service per year

Economic Plan

- Major component of costs is material costs



Economic Plan



- Stage One
  - 20 units per month
- Stage Two
  - 1000 units per month
- Stage Three
  - 3000 units per month
- Stage Four
  - 6500 units per month

Economic Plan - Funding

- Funding
  - Government of Bangladesh - essential
    - http://www.bangladoot.org
  - World Bank

  - Asian Development Bank (ADB)
  - United Nations International Children's Fund (UNICEF)
    - http://www.unicef.org/bangladesh/wes_420.htm
  - United States Agency for International Development (USAID)

Conclusions

Topic	Cost	Detail
Initial Installation	$1140	
Yrly. Maintenance (Including Main. Costs)	$5.5	
Per Village	$5,600	1000 People
Per District (Chandpur)	$1,960,000	350,000 People
Phase 1 > 50 ppb (over 12 year plan)	$150 million	To mitigate for 30 million people
Phase 2 > 10 ppb (over 10 year plan)	$233 million	To mitigate for 50 million people

Any Questions

?