Department of Biosystems and Agricultural Engineering
MICHIGAN STATE UNIVERSITY

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Biosystems Design Projects

Water Sanitation in Rural Amazon Communities

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Background

Dr. Briceno is a physician based in Iquitos, Peru, a major city next to the Amazon River. Over recent decades, Amazon River water quality has deteriorated due to factors such as:

- Deforestation
- Agricultural Runoff
- Improper Mining Techniques
- Oil Spills

Table 1. 2022 Water Quality Measurements in Marañón/Solimões region of the Amazon River Basin and relevant standards/regulations.

Water Quality Metric	Amazon River (Mean/Std Dev)	WHO Guideline	SSHR / SUNASS Regulation	Other Guidelines
pH [-]	6.85/0.96	6.5 < pH < 8.5	6.5 < pH < 8.5	
Dissolved Oxygen [mg/L]	6.30/2.44	N/A	N/A	4 < DO < 8
BOD5 [mg/L]	9.22/21.59	N/A	BOD5 < 5	
Electrical Conductivity [µS/cm]	101.41/ 123.8	N/A	N/A	EC < 1500
COD [mg/L]	36.63/ 41.84	COD < 10	N/A	COD < 4
Total Phosphorus [mg/L]	0.50/14.90	N/A	N/A	P < 10
Total Nitrogen [mg/L]	1.79/1.74	N < 50	N < 50	
Turbidity [NTU]	130.20/ 411.7	NTU < 5	NTU < 5	
Total Coliform Bacteria [MPN/100mL]	3065.83/ 10253.83	0 MPN	0 MPN	

As a result, poor village communities outside the city without access to modern water treatment methods or healthcare experience worsening health conditions: diarrhea, enteric diseases, ringworms, malnutrition, etc.

Goal: Design a feasible water sanitation system to implement in the villages that will mitigate the prevalence of waterborne illness. The 3 major deficiencies in water quality, highlighted above, will be prioritized. Additionally, the system must supply the minimum amount of water used per household, 86 L/ day.

Objectives

Due to technological, cultural, and financial factors, the team sought to:

- Minimize annual costs associated with owning a water sanitation system to less than 4% of the annual income of a household living under Peru's extreme poverty threshold
- Provide water that meets national and international guidelines
- Minimize infringing on cultural/societal practices and beliefs
- Maximize the lifespan of the system to over 5 years

Constraints

The most significant barriers the team sought to work around were:

- Extreme poverty throughout the village communities (the equivalent of $800 USD per household per year)
- Costly imports resulting from 2+ hour boat trips being the only way to access the villages
- Lack of electricity
- Unsanitary housing environment
- Community-wide hesitation to accept change

Design Alternatives

A diverse set of 4 design options were considered in addition to biosand filtration:

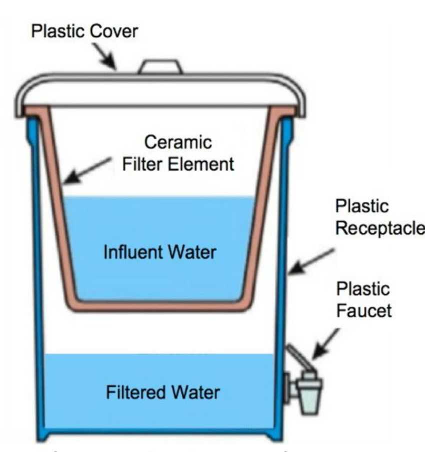

Figure 1. Ceramic filtration.

Figure 2. Chlorination.

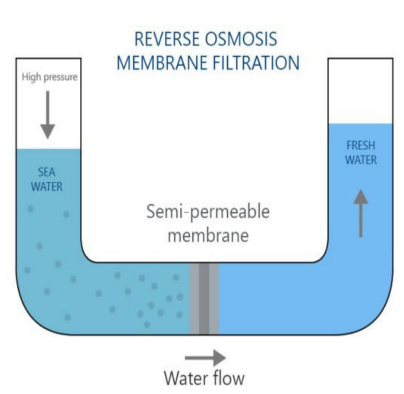

Figure 3. Membrane separation.

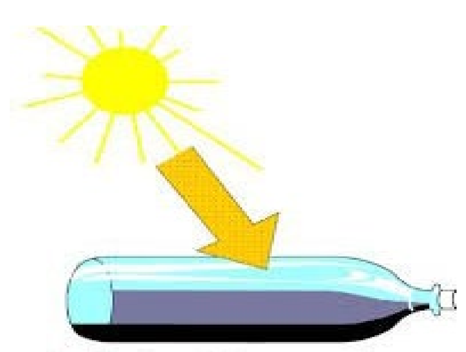

Figure 4. Solar water disinfection.

Each alternative was evaluated based on the following criteria:

- Efficiency in addressing the most problematic water quality areas
- Sustainability with regards to longevity and self-sufficiency
- Cost of initial and recurring capital investments
- Ease of use regarding foreign technology
- Maintenance requirements and associated safety risks

Selected Design

A 4-step multi-barrier approach was chosen, comprised of the following steps and illustrated in Fig. 5:

1. Pre-filtration gravity sedimentation
2. Biosand filtration
3. Post-filtration chlorination
4. Storage in an air-tight water dispenser

The primary mechanism for this design is biosand filtration, which uses both mechanical and biological processes to purify water:

1. As water trickles down the filter body, suspended sediment and other particles are trapped by the fine sand grains
2. Subsequent layers of larger-diameter sand and gravel prevent mixing of layers and pollutants leaving through the filter's effluent
3. After ~1 month of regular use, aerobic and anaerobic bacteria populations culture within the sand, consuming nutrients in the water while preying on pathogens and viruses.

Biosand filters have been shown to achieve removal rates of pollutants at magnitudes displayed in Table 2.

Table 2. Field-generated Pollutant removal rates [1, 2].

Pollutant	Removal Rate
Nitrates	24.0%
Phosphates	66.2%
Magnesium	56.9%
Fluorides	25.7%
Calcium	32.4%
Chlorophyll A	62.2%
Turbidity	93.6%
E. coli, Bacteriophage MS2, Bacteriophage PRD1	99%
Viruses	70%

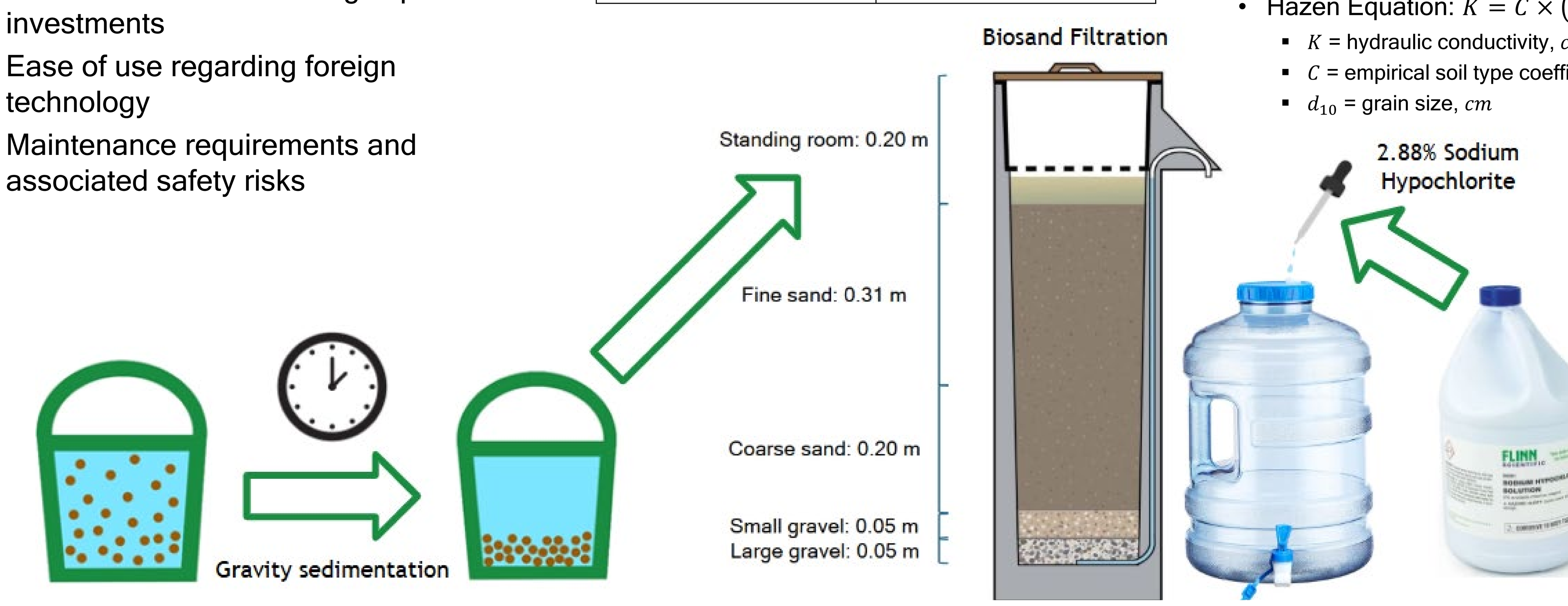

Figure 5. Final design diagram.

Design Parameters

Alterations were needed to ensure harmonic integration of the 4 process steps, requiring mathematical modeling:

Prior to filtering, gravity sedimentation is used to reduce the TSS concentration of the water to 50 mg/L to reduce clogging.

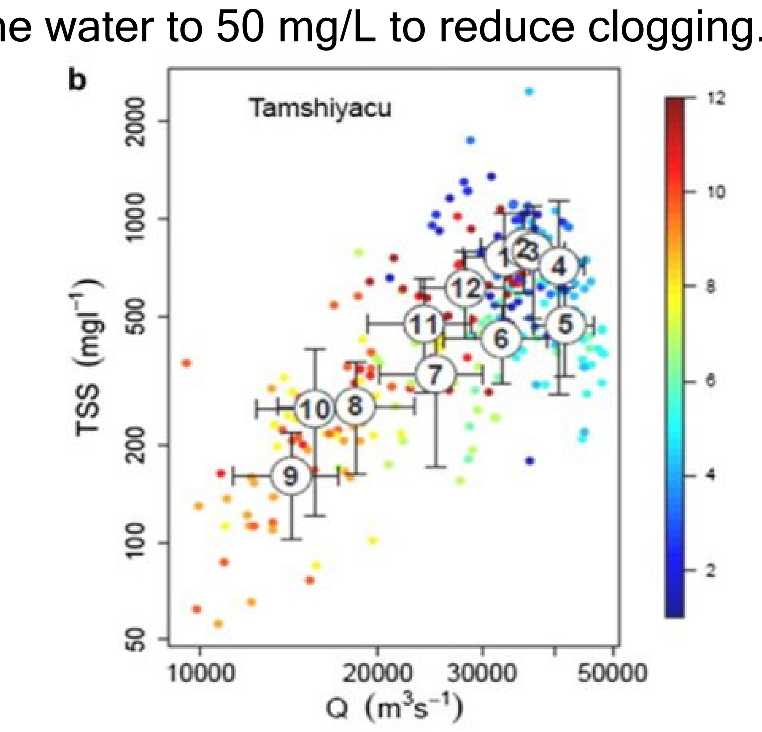

Figure 6. Amazon River flow rates and TSS concentration by month, measured upstream of Iquitos [3].

The following equations were used to determine the time required for sedimentation (48 min):

- Stoke's Law: $v_s = \frac{d^2(\rho_p - \rho_f)g}{18\mu}$ [3]
  - v_s = settling velocity, m/s
  - d = particle diameter, m
  - ρ_p = particle density, $\frac{kg}{m^3}$
  - ρ_f = fluid density, kg/m^3
  - g = acceleration force, m/s^2
  - μ = fluid dynamic viscosity, $Pa * s$
- First-order sedimentation: $TSS(t) = TSS_0 e^{-\frac{k}{t}}$ [3]
  - $TSS(t)$ = desired TSS concentration, $\frac{mg}{L}$
  - TSS_0 = initial TSS concentration, $\frac{mg}{L}$
  - k = rate constant, $\frac{v_s}{h}$, s^{-1}
  - t = time, s
- Filter media grain diameter:
  - Fine sand: 0.1 - 0.7 mm
  - Coarse sand: 0.8 - 1.2 mm
  - Small gravel: ½"
  - Larger gravel: 1"

The following equations were used to determine the flowrate (298 L/day) and hydraulic residence time (9.75 hr) of the water through the system:

- Hazen Equation: $K = C \times (d_{10}^2)$ [4]
  - K = hydraulic conductivity, cm/s
  - C = empirical soil type coefficient, $cm^{-1}s^{-1}$
  - d_{10} = grain size, cm
- Equivalent Hydraulic Conductivity: $K_z = \frac{d}{\sum_{i=1}^{n} \frac{d_i}{k_i}}$ [5]
  - K_z = equivalent hydraulic conductivity perpendicular to the filter layers, $\frac{m}{hr}$
  - d = total thickness of all layers, m
  - d_i = thickness of the individual layers, m
  - k_i = hydraulic conductivity the individual layers, $\frac{m}{hr}$
- Darcy's Law: $Q = -K_z A \left(\frac{h}{L}\right)$ [5]
  - Q= flowrate, $m^3/_{hr}$
  - A = cross-sectional area, m^2
  - h = head loss, m
  - L = length of the filter layers, m
- Hydraulic Residence Time: $HRT = \frac{V}{Q}$
  - HRT = hydraulic residence time, hr
  - V = volume, m^3

Lastly, a chlorination dose of 0.05-0.1 mL/L sodium hypochlorite was chosen based on literature.

Economics

Table 3. Bill of materials for complete water sanitation system. The price of necessary equipment is not included.

Material	Quantity	Unit Price	Total Price
Plastic bucket	1	$3.98/ part	$3.98
32-Gallon HDPE trash can with lid	1	$24.97/ part	$24.97
1/2" PVC piping	3 ft	$0.36/ ft	$1.08
PVC 90-degree elbow joints	3	$0.54/ part	$1.62
PVC end cap	1	$0.56/ part	$0.56
1/2" PVC female plug	1	$2.26/ part	$2.26
1/2" PVC male socket	1	$1.18/ part	$1.18
1.5" O-ring	1	$0.83/ part	$0.83
Coarse Sand	140 lb	$0.0135/ lb	$1.89
Fine sand	215 lb	$0.0175/ lb	$3.76
Small gravel	42 lb	$0.11/ lb	$4.62
Large gravel	42 lb	$0.1056/ lb	$4.44
Sealable plastic water storage container	2	$37.99/ part	$75.98
Sodium hypochlorite solution	1	$32.00/ gal	$32.00

The bill of material excluding necessary equipment for the construction of the final design in listed in Table 3. The cost incurred by the multi-barrier approach includes:

- Sanitation system price: $159.17
- Labor price: 16.72 PEN/ hour/ person
- Equipment price: $281.57

The sanitation system price is just under 20% of the annual income of a household living under Peru's extreme poverty threshold. The cost of the sanitation system will be prorated over the lifespan of the system to ensure affordability, costing only 4% of a household's annual income per year.

Select References

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