Pilot Study of Horizontal Roughing Filtration in Northern Ghana as Pretreatment for Highly Turbid Dugout Water

by

Tamar Rachelle Losleben

B.A. Environmental Science and Engineering
Rice University, 2004

Submitted to the Department of Civil and Environmental Engineering
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ABSTRACT

In Northern Region Ghana (NRG), highly turbid rainwater runoff and intermittent streams are collected in earthen dams called dugouts. These dams serve as many communities' main source of drinking and domestic water despite their physical and microbial contamination. Slow sand filtration (SSF), a low-cost technology for treating microbial contaminated drinking water is only recommended for water < 50 NTU. Two research objectives were established to address this issue: to characterize dugout particle sizes and distribution and to test a pilot horizontal roughing filter's (HRF) effectiveness at removing turbidity from highly turbid dugout water. Among the four dugouts tested in NRG, they typically have high concentrations of non-setttleable colloidal (< 1μm) and small supracolloidal particles (< 10μm). In addition, a pilot HRF at Ghanasco Dam in Tamale, NRG was conducted using three 7m tubes filled with three sizes of granite gravel, local gravel, and broken pieces of ceramic filters arranged by decreasing size. The pilot study was run for 52 days to test if HRF could reduce the high turbidity (305 NTU) to < 50 NTU to make SSF a viable option. There were a number of promising outcomes: the best performing media, the granite gravel, by removing an average 46% of the influent turbidity (filter coefficient $\lambda = 0.002\ \text{min}^{-1}$), produced an average effluent turbidity of 51 NTU which almost achieved the goal of < 50 NTU. The granite gravel HRF removed twice as much turbidity (46%) as plain settling (25%). Overall, the granite gravel removed 76% and 84% of the influent turbidity according to the settling test and pilot HRF data respectively. Three recommendations derived from this pilot HRF study are (1) to monitor dugout water quality, (2) to investigate media and particle properties to enhance colloidal particle removal (3) to modify the HRF to effectively remove very high dry season turbidities and likely even higher rainy-season turbidities from dugout water.

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Figure 1 Water collection in Northern Ghana

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ABBREVIATIONS

AMURT	Ananda Marga Universal Relief Team
CFU	Colony forming unit
CINARA	Centro Inter-Regional de Abastecimiento y Remoción de Agua
BNHP	Blue Nile Health Project
D	Local gravel media for Ghanasco pilot HRF
DALYs	Disability Adjusted Life Years
DRFS	Downflow roughing filters in series
DyGF	Dynamic gravel filter
EAWAG	Swiss Federal Institute for Environmental Science and Technology
G	Granite gravel media for Ghanasco pilot HRF
GDWQ	Guidelines for Drinking Water Quality
GWEC	Guinea Worm Eradication Campaign
GWSC	Ghana Water and Sewerage Corporation
HRF	Horizontal roughing filter
MDG	Millenium Development Goals
NGO	Nongovernmental organization
NRG	Northern Region Ghana
NTU	Nephelometric turbidity unit
O&M	Operations and maintenance
P	Pieces of ceramic Kosim filters used as media in the Ghanasco pilot HRF
PCVL	Peace Corps Volunteer Coordinator
PHW	Pure Home Water
RF	Roughing filter
SANDEC	Water and Sanitation in Developing Countries
SSL	Soil screening level
SSF	Slow sand filtration
TDC	Town Development Committee
TSO	Peace Corps Tamale Sub Office
TU	Turbidity units
UGFS	Upflow gravel filter in series
UGFL	Upflow gravel filter in layers
VRF	Vertical roughing filtration
WHO	World Health Organization

1.0 Introduction

1.1 The Need for Improved Water and Sanitation

Awareness of the direct impact adequate water and sanitation has on the spread of waterborne diseases, revolutionized public health and city planning in major cities in Great Britain and the United States in the late 19th century. Previously the commonly accepted atmospheric theory led people to believe that miasma, or bad air, escaped from the "bowels of the earth" and poisoned people with diseases such as cholera. It was in fact during a London cholera outbreak in 1849 that Dr. John Snow noticed a pattern in the location of cholera victims with relation to a local drinking water well. After careful collection and analysis of epidemiological data, he surmised that cholera was waterborne. As a result, to put a halt to the fatal cases, the handle of the water pump was removed to effectively prevent use of the contaminated source. As Dr. Snow continued his work, not only was the link between ingesting contaminated water and contracting cholera further confirmed, but it became apparent that a key to preventing such illness was selecting the best water source available (Okun, 1996). Finding adequate sources that provide sufficient quantities of uncontaminated water is becoming increasing challenging as the world's population grows, the climate changes, and lands continue to be deforested.

Though high-income countries have significantly improved their life expectancy and curbed the spread of waterborne diseases since the sanitary revolution of the 1800s by extending access to cleaner sources of water, adequate sanitation, and hygiene education, scarce funding, administrative structure, and availability of local technical expertise are some of the factors that limit advances in low or middle-income countries. Many such countries experience water shortages because the cost of accessing cleaner groundwater is prohibitive and surface water that is available often fluctuates seasonally and has high levels of microbial contamination and turbidity[1]. In hope of making clean drinking water accessible globally, in 1977 at the UN Water Conference at Mar del Plata, 1981-1990 was declared the first "International Decade for Clean Drinking Water." Since 1990, a concerted global effort gave an additional billion people access to safe water. Unfortunately, almost an equivalent number of people (1.1 billion) still lack access to potable water. The remaining people without access to potable water may be even harder to reach because those communities with the most accessible, uncontaminated water sources may have been targeted first. Though the job is not easy, the basic need for potable water must be met. Seeking to lessen the disease burden caused by waterborne disease, the UN General Secretary Kofi Annan announced at the 58th Session (A/Res/58/217) that the second "Decade of Water for Life" would begin in 2005 especially striving for greater participation of women as managers of water.

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[1] Turbidity is an "indirect measure of the particulate matter in water" which determines the relative amount of particles present (AWWA, 1999). It does not directly measure the type, number or size of particles present but rather the cloudiness as a measure of the amount of light that is able to pass through the fluid. The most common unit used is the nephelometric turbidity unit (NTU) but field experiments are some times completed using a simple instrument which gives turbidity measurements as turbidity units (TU).

The disparity between the advancement of appropriate drinking water treatment and sanitation in high income countries in comparison to the lack of it in low and middle income countries is apparent in Figure 2 (WHO, 2002). In extremely underserved areas such as sub-Saharan Africa and the Pacific where drinking water coverage rates drop to 58% and 52% respectively, the burden of diarrheal disease is extremely high (UNICEF, 2007). Global leaders in public health considering such high prevalence of diarrheal disease unacceptable, challenged world leaders to meet the UN Millennium Development Goal 7 (MDG); to "half, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation."(UN-NGLS 2006) While much progress has been made in improving access to drinking water, Figure 3 depicts the numerous countries not on track to meet MGD 7. To meet such an ambitious goal, cost-effective, appropriate, sustainable interventions to improve drinking water quality and sanitation must be considered. Developing water treatment processes appropriate for low and middle income countries is pivotal in beginning to relieve this tremendous burden of disease that very much depends on levels of socioeconomic development (WHO, 2006).

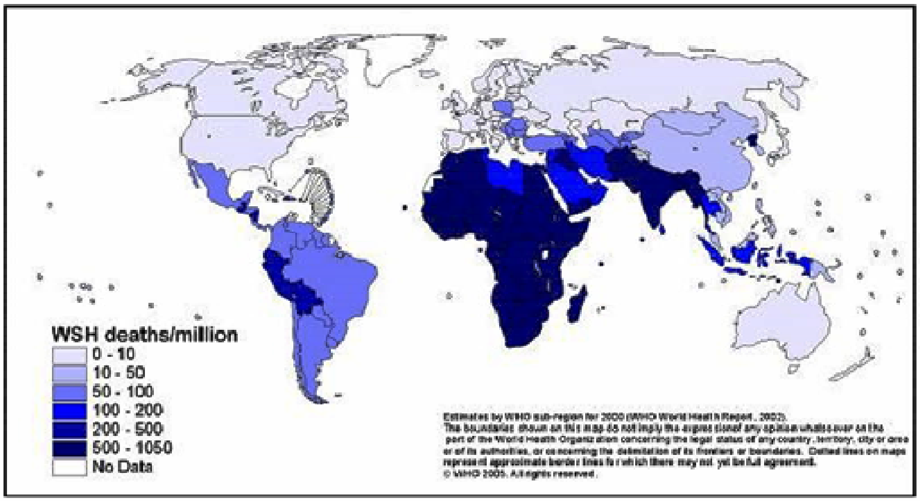

Figure 2 Deaths caused by unsafe water, sanitation, and hygiene for 2000 by Country (WHO, 2002)

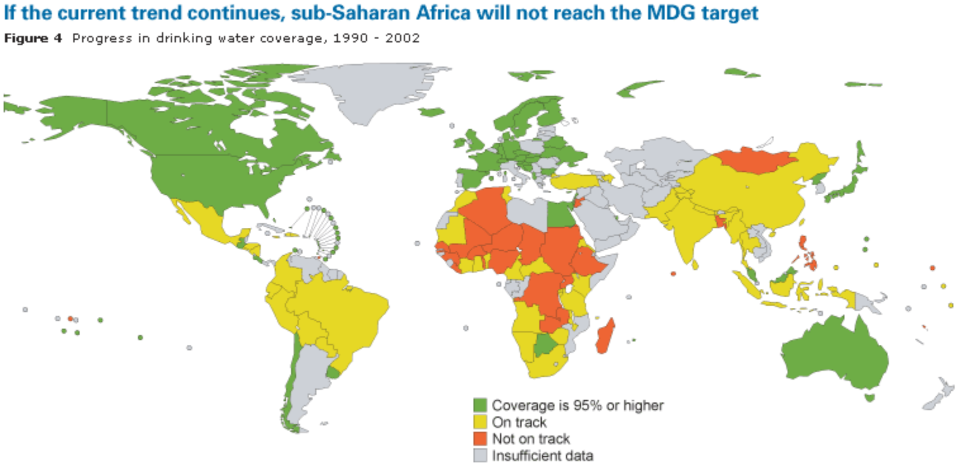
If the current trend continues, sub-Saharan Africa will not reach the MDG target

Figure 4 Progress in drinking water coverage, 1990 - 2002

Figure 3 Meeting the MDG target for drinking water coverage (UNICEF and WHO, 2004)

Many rivers, lakes, and streams worldwide exhibit seasonally high turbidities particularly in tropical climates where heavy, rainy season runoff carries silt into the surface water (Okun & Schulz, 1984). Possible turbidity sources include domestic sewage, urban and agricultural runoff, stream bank erosion, wind transport of fine particles, and construction activity (AWWA, 1999). As population growth increases pressure on natural resources through the need to harvest firewood, produce charcoal, expand urban areas, and extend agricultural lands, water worldwide may become more turbid. At the same time, climate changes' effect on the intensity and duration of rainfall and windy, dusty weather can further elevate surface water turbidity levels.

The concern surrounding highly turbid water in developed countries primarily arises from the problem it poses to effective disinfection and secondarily to problem of sediment accumulation in distribution pipes and pipe corrosion. Highly turbid water can reduce the effectiveness of common water treatment methods such as slow sand filtration (SSF) and chlorine disinfection. In addition, turbidity of piped water above 1 nephelometric turbidity unit (NTU) may indicate that the distribution system needs to be flushed and the pipes checked for corrosion (AWWA, 1999). High turbidity is a worldwide challenge. However, turbidities in tropical countries are especially high and may range from 100 NTU to above 1000 NTU. This is true in Northern Region, Ghana, the location of this study, where consumers face limited availability of highly turbid surface water drinking supplies. In this case and in others like it, a sustainable, low-cost, appropriate, first stage of water treatment is needed to reduce the turbidity to acceptable levels.

1.2 WHO Guidelines for Drinking Water Quality

Since 1958, the World Health Organization (WHO) has established and published up-to-date drinking water quality guidelines applicable globally to developed and developing countries. The most current 3rd Edition WHO *Guidelines for Drinking Water Quality* (GDWQ) was published in 2004.

The ultimate goal of drinking water treatment is to provide the beneficiary with safe water free of harmful chemicals and pathogens such as bacteria, viruses, protozoa, and helminthes that spread infectious diseases. Drinking water is an important transport vehicle for pathogens by the fecal-oral route. Other pathways include contamination of food, hands, utensils, and clothing (WHO, 2004, p. 29). Though the public health and environmental engineering community still debates the relative importance of hygiene, sanitation, water quality, and water quantity in the spread of gastrointestinal infectious diseases, the WHO GDWQ are widely accepted as the foundation for regulation and standard-setting to insure safe drinking water.

1.2.1 WHO Turbidity Guidelines

While the WHO GDWQ state that the median turbidity should be below 0.1 NTU for effective disinfection, they no longer recommend a health-based guideline value for turbidity in the latest GDWQ (WHO, 2004, p.271). Although turbidity influences the microbial water quality, turbidity itself does not necessarily cause adverse health affects. The WHO does, however, recognize a correlation between turbidity and microbial contamination because they observe that, "Sporadic high turbidities in source water can overwhelm treatment processes allowing enteric pathogens into treated water and the distribution system." (WHO, 2004) In addition to water being free of microbial contamination, having an acceptable taste, and appearance are also important parameters for consumers. Consumers usually accept the appearance of water with turbidity less than 5 NTU (WHO, 2004).

1.2.2 WHO Microbial Contamination Guidelines

Because of the tremendous global burden of gastrointestinal infectious diseases, priority is given to ensuring the microbial safety of water. Faecal-oral pathways are not the only mode of transmission. Source water can also provide habitat for water-grown vectors like Guinea worm (*Dracunculus medinensis)* or Schistosomiasis (*bilharziasis*) which are spread respectively by ingestion of a water flea carrying the Guinea worm cyclops or the trematode worm shistosome penetrating the skin of the human host. Another avenue for risk, especially for immune-compromised individuals is bathing because they can develop various skin, eye, ear, nose, and throat infections through having contact with contaminated water (WHO, 2004). From a public health standpoint, important microbial growth factors to consider are the organisms' persistence in water supplies, resistance to chlorine, relative infectivity, and health significance. The most widespread pathogens and parasites are highly infectious and either find water to be a hospitable environment for reproduction or are able to resist decay outside the body. The most common life-threatening, water-borne diseases include typhoid, cholera, and hepatitis A.

WHO guidelines state potable drinking water, treated water entering a distribution system, and treated water in a distribution system must not have detectable *Escherichia coli* (*E. coli)* or thermotolerant coliform bacteria present in any 100-ml sample (WHO, 2004). *E. coli* bacteria, commonly found in the lower intestine of warm-blooded animals, are used as indicators of fecal pollution. Total coliform is not a sufficient indicator of fecal contamination because many bacteria, especially in tropical areas, have no sanitary significance. Total coliform, however, is a good indicator of treatment efficacy. Immediate action must be taken if *E. coli* are present. Keeping *E. coli* out of rural water systems can be challenging in developing countries where fecal contamination is extensive. In this case, a medium-target should be set to encourage progressive improvement of water supplies via the development of water safety plans.

1.2.3 Removal and Disinfection of Waterborne Pathogens

Slow sand filtration (SFF) and chlorination are two of the most common, low-cost and easy-to-maintain water treatment systems for surface waters in developing countries.

1.2.3.1 Slow Sand Filtration and Turbidity

Slow sand filtration is inexpensive treatment method that can be constructed out of mostly local materials, is easily operated and maintained, and has a tremendous ability to improve drinking water quality in developing countries by removing between 2 to 4 log (99 to 99.99%) of microorganisms (Wegelin, 1996). Removal of organic material and pathogenic organisms in SSF (such as protozoa, bacteria, viruses, and helminthes) from low turbidity raw waters depends on the *schmutzdecke*, a thin layer on the top 0.5 to 2 cm of sand where biologically-active microorganisms trap and digest particulate matter.

Slow sand filters are cleaned manually by removing the top dirty layer of sand. This process typically takes one to two days and then the filter must ripen before the effluent is safe to use. A SSF can run for several months if water contains low concentration of algae and low turbidities. Conversely, high turbidities and high concentrations of algae can quickly clog the filter resulting in short filter runs and burdensome operation and maintenance costs.

Sensitivity to high turbidities means that SSF requires pre-treatment if the raw water turbidity is greater than 50 NTU for longer than a few weeks (Okun & Schulz, 1984). While Okun & Schultz specify an influent turbidity < 50 NTU for effective SSF, literature differs in what are considered acceptable turbidities for SSF. The usual required influent turbidities range from 5 NTU to 50 NTU (Galvis, Visscher, Fernández, & Berón, 1993). Respectively, Martin Wegelin from the Swiss Federal Institute for Environmental Science and Technology (SANDEC) and Gerardo Galvis from the Centro Inter-Regional de Abastecimiento y Remoción de Agua (CINARA) recommend a 20-30 NTU and 20 NTU limit for the influent of SSF (Wegelin, 1996) (Galvis et al., 1993). Huisman and Wood in 1974 found the optimum purification occurs when the turbidity is below 10 NTU (Okun & Schulz, 1984). More recently, Cleasby (1991) determined that influent SSF turbidity should be no greater than 5 NTU (as cited by Galvis et al, 1993). In other words, SSF requires fairly good influent water and, in general, should not be used for treating highly turbid water > 50 NTU.

Even when turbid water is pretreated, fine particles such as clay can quickly clog the filter bed, cause extreme increases in head loss, and create undesirable conditions in the active biofilm layer in the filter bed (Galvis et al., 2006). Short peaks in turbidity can force the active biofillm deeper into the sand filter bed and, as a consequence, reduce the SSF's removal of pathogenic microorganisms. Although a SSF can be effective, such limitations on its efficacy are important to note and are sometimes buried in the literature. Other more cited problems, including clogging and reduced filter runs, are common when SSF treats water with a high quantity of very small colloidal particles (Galvis et al., 2006). If the raw water turbidities are lowered, SSF could provide a simple solution for facilities that do not want to use coagulants.

Advantages

The use of SSF in developing countries can be very advantageous and provide another safety barrier prior to chlorination and consumption (Okun & Schulz, 1984):

- Construction costs for SSF are very low in comparison with many other community-based treatment systems.
- The simplicity of the design and operation mean that very little technical supervision is required to run the SSF.
- Maintenance mainly consists of cleaning the beds, which can be completed by unskilled labor.
- Materials and equipment can be purchased locally.
- No chemicals are required.

- If gravity head is available, then the system can be run without power.
- Slow sand filtration can accommodate some fluctuations in the raw water quality and temperature as long as the turbidity does not increase too much and only lasts a short time.
- During the cleaning process, large amounts of washwater are saved.
- If chlorine is applied, SSF removal of organic material allows for a reduced dosage of chlorine and some cost savings.

Disadvantages

In tropical climates disadvantages include (Okun & Schulz, 1984):

- Algae blooms that choke the filter bed;
- Maintenance of the biological layer which sometimes is sensitive to heavy concentrations of colloids and some toxic industrial wastes;
- Filters that only have intermittent flows are more at risk of becoming anaerobic because the stagnant, turbid water sitting on top of the filter inhibits oxygen from reaching the beneficial microorganisms;
- Careful attention needs to be paid to making sure filters do not become anaerobic because this would cause taste and odor issues.

1.2.3.2 Chlorine Disinfection and Turbidity

Chlorine compounds (hypochlorites) are effective at killing pathogenic organisms, available in most developing countries, and are fairly moderate in cost. An added benefit is that chlorine residual can prevent recontamination of treated water in the distribution system. However, raw waters with high turbidities complicate the disinfection process. More turbid water has a higher chlorine demand because it requires more chlorine to oxidize organic matter present. Therefore, the WHO recommends influent turbidity be less than 0.1 NTU prior to chlorination (WHO, 2004). In emergency situations less than 20 NTU is acceptable (Godfrey, 2005).

Not only does highly turbid water require longer chlorine contact times and the addition of more chlorine compounds, but disinfection may not be effective enough against pathogens within flocs or particles. The WHO states that “high levels of turbidity can protect microorganisms from the effects of disinfection, stimulate the growth of bacteria and give rise to a significant chlorine demand.” (WHO, 2004, p. 33) Although the presence of organic matter and chlorine could react to form disinfection byproducts, the WHO warns that “disinfection should not be compromised in attempting to control disinfection by-productions (DBPs)” (WHO, 2004, p.33). The main goal is to provide pathogen-free drinking water and thereby reduce the incidence of waterborne illness.

2.0 Objectives

A large amount of drinking water in Northern Region Ghana (NRG) comes from dugouts[2] which are unreliable, of poor microbial quality, and extremely turbid sources. The root of the problem lies in the dugouts as water sources. Until dugouts are identified and improved as storage basins, drinking water quality at the household and community scale will persist. This problem is addressed in two related steps: testing dams' physical water quality in order to better understand the suspended particles' sizes and settling behavior, and testing a pilot horizontal roughing filter (HRF) to see if it can effectively pre-treat water prior to SFF. The ultimate goal is to improve dugouts as a surface water source. The author recognizes that improved water supplies for all is the aspiration and that groundwater via a borehole well is generally microbially safe and clean. However, such sources are difficult to locate and expensive to tap into. Conversely, surface water sources, although more inexpensive to access often contain turbid water with a high level of suspended clays. This thesis explores potential treatment of these dugout sources as a complement to ongoing borehole provision efforts in Northern Ghana.

2.1 Particle Size and Distribution of Dams

Knowledge about the type, size, and behavior of suspended particulate matter in the dams is pivotal to determining the main source of particles, how to prevent them from entering the dam water, and how to remove them from the dam water.

2.2 Ghanasco Dam Pilot HRF

In Northern Region Ghana, lack of appropriate technology to remove turbidity from the raw dugout water to a level adequate for subsequent SSF is an important piece of the problem. This thesis describes a pilot HRF tested at Ghanasco Dam, a dugout in the semi-urban area of Tamale (Figure 4), to see if, given the local particle sizes and distribution in the dam water, HRF can pre-treat the raw water to remove enough turbidity to make SFF a feasible option.

Figure 4 Image of Tamale, Ghana and Ghanasco Dam (http://maps.google.com/) (left) and the shore of Ghanasco Dam (right)

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[2] In this study, dugouts will be used synonymously with dams that catch and store rainwater and water from intermittent streams.

3.0 Particle Properties of Highly Turbid Water

Difficulties arise in the treatment of highly turbid water because particulate matter can enhance microbial growth, mask detection of microorganisms during water quality testing, interfere and make the SSF and disinfection processes more expensive (Health Canada, 2001). The WHO suggests the more turbid the water, the greater the risk of acquiring a gastrointestinal illness. An epidemiological study completed by the Public Health Agency of Canada, Health Canada, from 1992 to 1998 supported a direct relationship between the number of gastrointestinal-related health outcomes in the Greater Vancouver area and turbidity levels in water 1 to 39 days earlier (Health Canada, 2001). It is believed that this relationship can be explained by microbe's ability to use particles as a suitable habitat for growth and reproduction (AWWA, 1999, 18.19). Such evidence confirms the WHO GDWQ's conclusions that removing particles and turbidity reduces the protozoal cysts and oocysts (WHO, 2004). Therefore, in general, the probability of gastrointestinal disease increases with the presence of turbidity.

3.1 Sources of Particles

Although rainwater usually carries few particles, rain runoff carries suspended particles into the dugouts worsening the water's physical water quality. Other sources of turbidity include algal growth (Figure 5), water collection (Figure 5), fishing (Figure 6), and humans and animals entering the dam (Figure 7). Additional sources of turbidity include erosion of loose soil, deposition of dust from the air, and wind advective mixing of lake sediments. Physical characterization of particle size and their relative distribution will greatly vary depending on the climate, soil type, the slope of the area, and land use practices.

Figure 5 Vitting Dam (left) and fetching water from Tugu Dam, Tamale
Photo Credit: Melinda Foran (September 2006) (left), Susan Murcott (January 2006) (right)

Figure 6 Fishermen at Libga Dam, Savelugu (left) and children swimming in Diare Dam, Savelugu during the rainy season
Photo Credit: Melinda Foran (September 2006)

Figure 7 Livestock drinking from Ghanasco Dam (left) and Kunyevilla Dam (right) during the dry season (January 2008)

3.2 Particle Sizes

The type of particles present and their relative size distribution depend greatly on the land use and management practices of the catchment areas. Particles vary in their sizes and settling properties and are either inorganic or organic (Figure 8 and Table 1). Levine found that very few organic materials are less than 0.1μm in wastewater (Levine, Tchobanoglous, & Asano, 1985).

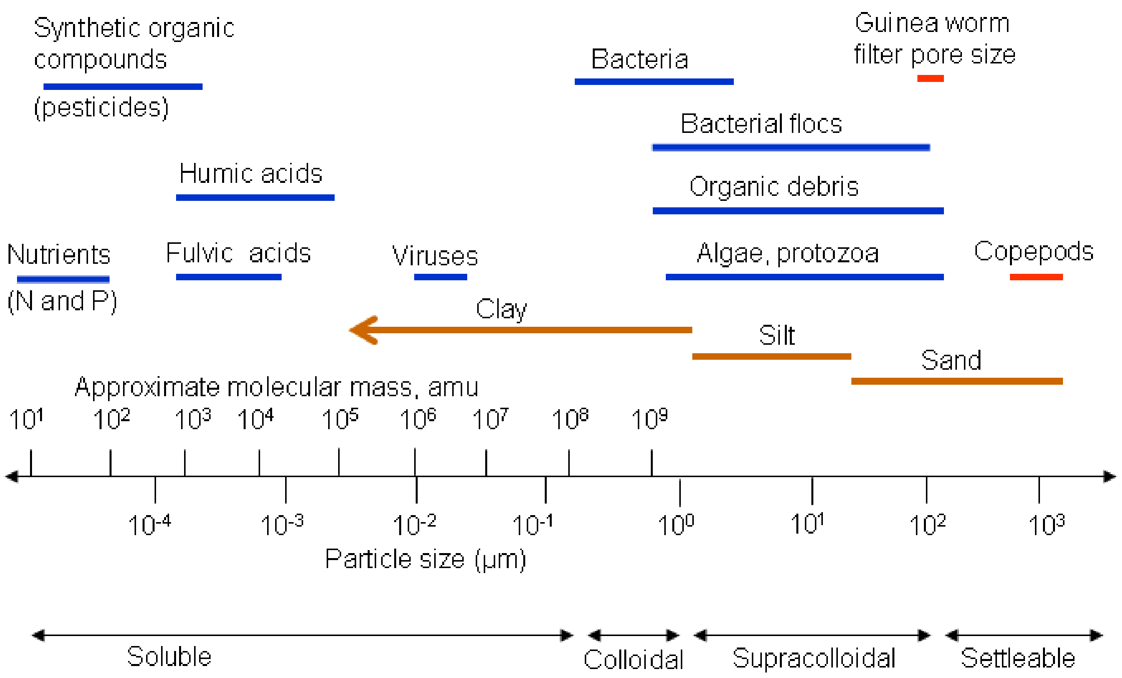

Figure 8 Typical particle sizes and their settling properties

Table 1 Particle Size Categories (Levine et al, 1991)

Size Categories	**Size**
Dissolved	<0.001μm
Colloidal	0.001-1μm
Supracolloidal	1-100μm
Settleable	>100μm

3.2.1 Inorganic Particles

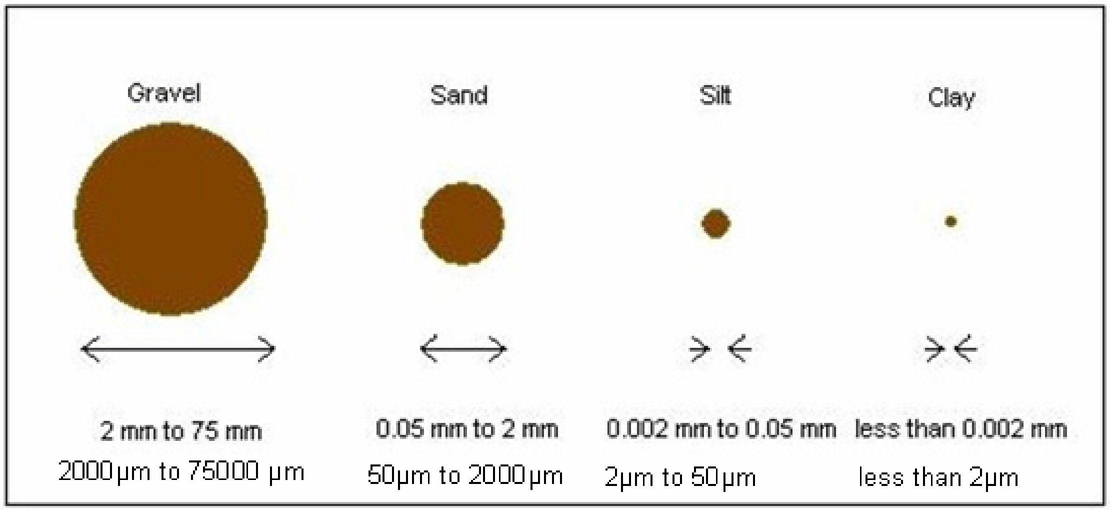

Figure 9 Soil particle sizes (http://techalive.mtu.edu/meec/module06/SoilClassification.htm)

Inorganic particles such as silt and clay (Figure 9) can be suspended in water because of their small particle size; 2µm to 50µm (supracolloidal according to Levine's classification in Table 1) and less than 2µm (small supracolloidal and colloidal) respectively. Supracolloidal silt particles have different atomic arrangements of minerals and are more settleable than clay particles. As colloidal particles, clay is smaller and is more likely to remain suspended in water. Depending on the type of clay, the particulates may form aggregates with naturally occurring aluminum and/or iron and magnesium. One example of this is ferrous iron which oxidizes to form ferric hydroxide giving the water a reddish-brown color (WHO, 2004); the presence of ferrous iron is the reason clay soils in NRG have a reddish-brown color. Clay soils are abundant in NRG. Table 2 shows the relative particle size characterization results for Ghanasco Dam (the site of this pilot HRF study) in Tamale, NRG. Sequential filtration tests (see Sections 6.2.3.3, 7.2.5, and 7.3.4) showed 59% of the particles in Ghanasco Dam are less than 1.2µm (colloidal). It is possible that clay particles carried into the dugout by runoff are responsible for the majority of this turbidity from particles less than 1.2µm.

Table 2 Ghanasco Dam Particle Characterization

Particle Size Categories	**Size**	**% Fraction of Turbidity**
Dissolved and colloidal	< 1.2µm	59%
Small supracolloidal	1.2–10µm	36%
Supracolloidal	10-20µm	8%

3.2.2 Organic Particles

Organic particulates can also be a large contributor to turbidity and perpetuate problems with microbial contamination as they provide potential habitat for microbes. Some organic particulates of concern include fecal cell debris, wastewater solids including aggregates of bacteria and virus, cyanobacteria and protective mats or algal cells (AWWA, 1999, 18.19).

4.0 Pretreatment Solutions for Removing Particles from Highly Turbid Surface Water

The appropriateness of pre-treatment options depends on the:

- Water source and its quality
- Beneficiaries' ability and willingness to pay
- Availability and cost of materials
- Complexity of the system
- Presence of a trained caretaker able to operate and maintain the system

Pretreatment options will be considered within this framework. The object is not to give a detailed outline of design criteria but rather to introduce different options for the removal of suspended matter. Source protection, plain sedimentation, storage, and roughing filtration (RF) are low-cost pretreatment options that could potentially improve the water quality of dugouts in Northern Ghana. Field studies were conducted in and around Tamale, Northern Ghana to insure the selection of a pre-treatment process appropriate for the specific raw water characteristics. The goal is that the pretreatment reduces the turbidity to be within the 20-50 NTU range or lower so that SSF can be effective.

Table 3 Conventional Methods of Pretreatment (Huisman and Wood, 1974 as cited by Okun and Schultz, 1984, p. 31)

Pretreatment	Turbidity Range (NTU)
Plain sedimentation	20 to 100
Storage	>1000
Roughing filtration	20 to 150

Table 3 categorizes pretreatment options according to raw water turbidity ranges. Although Table 3 suggests storage is appropriate for raw water with turbidities greater than 1000 NTU, it neglects two important variables: the raw water's specific particle size distribution and residence time. Additionally, according to Table 3, RF is only appropriate for raw water turbidities up to 150 NTU. These and other guidelines for pretreatment of turbid surface water will be reconsidered in subsequent sections of the present work.

4.1 Protecting the Source

If the best available water source is highly turbid, in most cases improving the management and protection of the water source could prevent some particulate matter from entering the source. Source protection is particularly important for surface water sources as they are easily contaminated through direct or indirect contact with humans and livestock. According to the WHO DWQG, a great impetus for preventing contamination is that less treatment will be required and so operational costs of any pretreatment system will be lower (WHO, 2004).

Improvements to the catchment area could apply the multi-stage barriers approach that usually includes (Okun & Schulz, 1984):

- Selection of the best available source;
- Protection of that source;
- Flocculation and sedimentation barrier;
- Filtration barrier and disinfection barrier.

The multi-stage barrier options following source selection and protection can vary with the availability of financial and technical resources. Inexpensive mitigation measures might incorporate physical barriers, such as fences, that limit the people and livestock that have direct access to the surface water, and reeds or foliage that act as a natural barrier and filter to particulate matter that is carried into the surface source through runoff. Natural plant barriers such as thorn bushes can be formed around basins to conceal and break wind effect and limit uncontrolled access to the surface water (Okun & Schulz, 1984). In addition, the intake's location and design can help to reduce the turbidity.

The comparison of two dams, Mafi Kumase Dam in Southern Ghana and Ghanasco Dam in Northern Ghana, illustrates how land use practices around a dam can impact its turbidity (Figure 10 and Figure 11). The banks of the dams differ. Mafi Kumase Dam has wetland reeds and vegetation along its shores and has a very low turbidity[3] of 9 NTU (7 TU). Conversely, Ghanasco Dam has banks that are of bare soil, void of foliage and have a dry season turbidity range[3] from 202 – 540 NTU (150 – 400 TU). This contrast illustrates how protection of surface water catchment areas may have a tremendous impact the turbidity of the dam water. Restricted entrance to and use of the dam water in the south could also partially explain the difference in physical water quality between the south and north (Table 4).

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[3] These turbidity ranges are based measurements taken in January 2008 with a DelAgua® turbidity tube in TU. A correlation between TU and NTU was found and used to convert TU to NTU (Appendix D: Relationship between Nephelometric Turbidity Units (NTU) and Turbidity Units (TU).

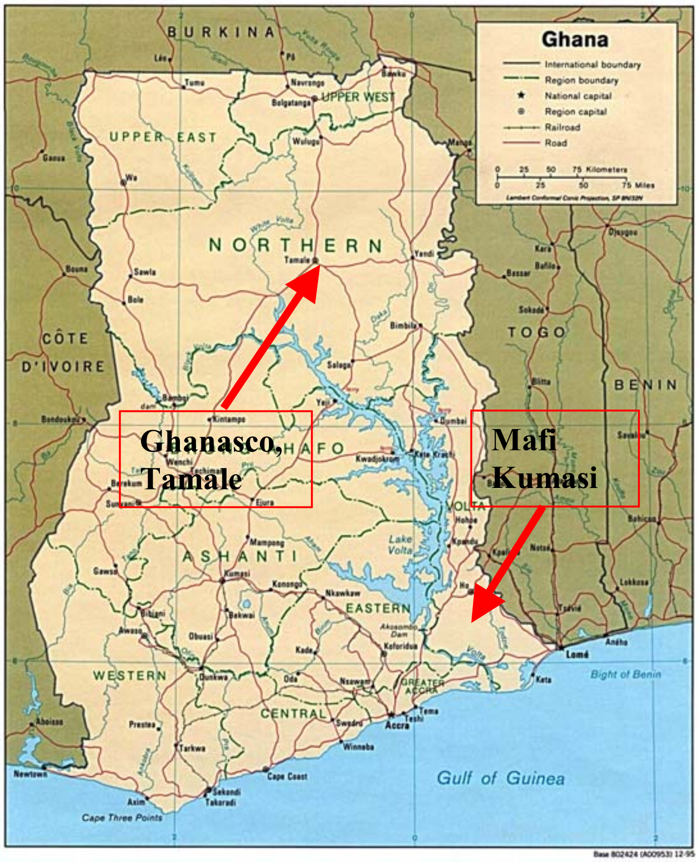

Figure 10 Location of dams, Ghana http://www.lib.utexas.edu/maps/africa/ghana_pol95.jpg

Table 4 Dry Season Turbidity Measurements for Two Dams in Ghana

Dam	**Region**	**Location**	**Turbidity**	**Date**
Mafi Kumase	Volta	Southern Ghana	< 9 NTU	2-1-08
Ghanasco	Northern	Northern Ghana	305 NTU	Average for January and February 2008

Figure 11 Mafi Kumase Dam in the South (left) and Ghanasco Dam in the North (right), Ghana

4.2 Plain Sedimentation

Plain sedimentation is a simple process of removing heavier and larger particles by gravity and the natural aggregation of suspended particles. The horizontal-flow sedimentation basin (Figure 12) is an efficient design because it does not necessarily require mechanical sludge removal or foreign equipment and uses unskilled labor for cleaning the tank. It requires very little maintenance work. It is possible to use unskilled labor in carrying out coagulation of particles prior to filtration, particularly in tropical developing countries. The advantages of plain sedimentation in developing countries are that turbidity is mainly due to soil erosion of silt soils which, due to their size, are settleable. Higher temperatures in tropical climates also improve settling by lowering the viscosity of water. In addition the removal of inorganic particles, enteric viruses and protozoa, which survive longer (weeks and months) in the environment, can be removed through settling and the predation of indigenous microbes. In practice in developing countries, high water demands often lead to overloading of the sedimentation tanks because rural communities don't have funds to expand tanks.

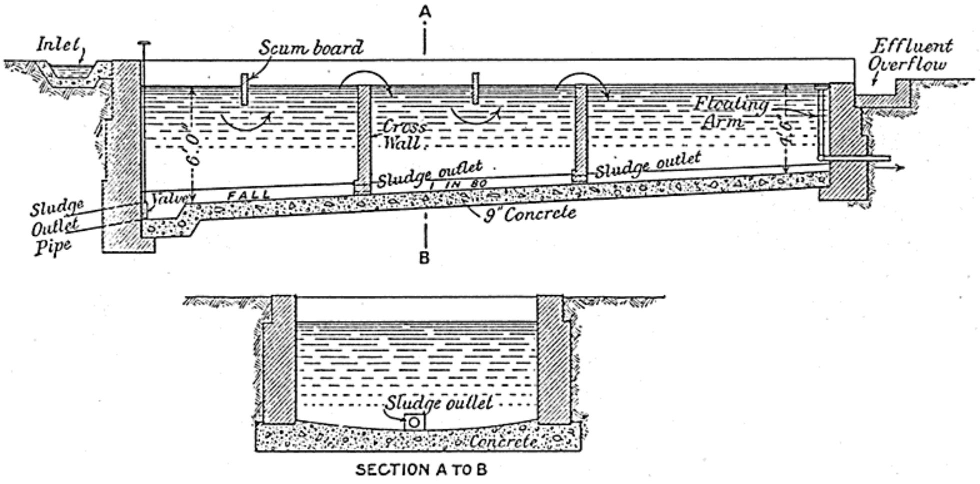

FIG. 4.—*See* Precipitating or Settling Tank (p. 335).

Figure 12 Settling tank (http://www.sewerhistory.org/images/bm/bme2/1910_bme204.gif)

Settling tanks may be an effective treatment step for some water; however, removal efficiencies are specific to the physical characteristics of each water source and depend on the particle size distribution, particle density, and water viscosity and temperature. Table 5 gives settling times that result in an order of magnitude removal for different sized particles. In Table 5 it is apparent that a reasonable retention time of hours or days rather than years limits plain sedimentation. With this information, Okun and Schluz (1984) calculated that plain sedimentation is suitable for water with turbidities formed by particles larger than 1μm with up to 500 NTU. Therefore, sedimentation may be ideal for supracolloidal particles (1-100μm) such as algae, bacteria, silt, and fine sand but it does not effectively remove colloidal and dissolved particles less than 1μm in size.

Table 5 Effect of Decreasing Size of Spheres on Settling Rate (Okun and Schultz, 1984, p. 32)

Diameter of Particle (µm)	Order of Size	Total Surface Area	Time Required to Settle
10,000	Gravel	3.14 cm^2	0.3 sec
1,000	Coarse sand	31.4 cm^2	3 sec
100	Fine sand	314 cm^2	38 sec
10	Silt	0.314 m^2	33 min
1	Bacteria	3.14 m^2	55 hr
0.1	Colloidal particles	31.4 m^2	230 days
0.01	Colloidal particles	0.283 ha	6.3 yr
0.001	Colloidal particles	2.83 ha	63 yr minimum

4.3 Earthen Water Storage Basin

Earthen waster storage basins (also referred to in this study as dugouts, dams, and runoff harvest ponds) are ecological, inexpensive, and highly effective at collecting rain runoff that would otherwise be unusable. The water storage basin acts as a large settling tank that stores still water for one week to a couple of months. Okun and Schulz (1984) state it could be the best treatment for removing particulate matter when the turbidity is over 1000NTU, especially when the particles are larger and denser. When particles are small and light, it becomes difficult to produce enough treated water because the particle settling times are too slow. Their low cost, easy maintenance and large storage capacity have made dugouts prevalent throughout Northern Region Ghana (NRG).

Okun and Schulz listed benefits of storing water (1984):

- Reduces the turbidity through natural sedimentation;
- Levels out sudden peaks in raw water quality;
- Reduces the number of pathogenic bacteria when storage is properly maintained;
- Improves the regularity of the water supply;
- Provides an alternative sources if the other source becomes contaminated or has a sudden fluctuation in turbidity.

Settling is the main particle removal mechanism at work in ponds[4] ; however, unlike horizontal settling tanks where water slowly flows through the system, there is less transport of water in a storage basin. The residence time of water in a storage basin is much longer than a settling tank. Table 6 shows the results of a study completed in Mosul, Iran on how effective long detention times can be at allowing particulate matter to settle (Okun & Schulz, 1984). One important detail that was excluded from the description of this study was the particle size distribution. From the fact that settling

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[4] In his book on water storage, Art Ludwig identifies three types of ponds (Ludwig, 2005):

- Dam – impoundment in a natural watercourse;
- Runoff harvesting ponds – open, earth-supported storage basins;
- Living ponds – natural ponds.

See Appendix B: Pond Characteristics (Ludwig, 2005) for a chart that explains more about these pond categories. In NRG, dams/dugouts are simultaneously both dams/runoff harvesting ponds.

caused over an 80% reduction in turbidity, it is probable that the particles sizes were fairly large; probably larger than 100µm.

Table 6 Turbidity Removal with Different Settling Times, Mosul, Iraq (Ahmad, Wais, and Agha, 1982 as cited by Okun & Schlutz, 1984, p. 35)

Initial Turbidity (NTU)	Turbidity Remaining (NTU) After 2 hr	Percent Turbidity Removal After 2 hr	Turbidity Remaining (NTU) After 3 hr	Percent Turbidity Removal After 3 hr
500	145	71 %	90	82%
1200	620	48%	120	90%
1800	450	75%	90	95%
2500	610	76%	120	95%

4.3.1 Storage Basin Design

Design criteria for runoff harvesting ponds should be based on local land availability, the natural topography, and a capacity assessment that accounts for water losses from evaporation and seepage. Flat sites, like those in Northern Region Ghana (NRG), are easier for pond construction. There are advantages to both smaller and larger ponds. Smaller ponds experience fewer problems with wind wave erosion on their shores. Larger ponds store water more economically. Usually the size of a runoff harvesting pond directly depends on the amount of runoff (Ludwig, 2005). Most runoff harvesting ponds in NRG are excavated and have raised rims around them so that very little uncontrolled runoff carrying particulate matter enters (Figure 13). In cases were seepage is a problem, the bottom of the basin may be lined with compacted clay[5] or some other impervious layer. While Okun and Schulz (1984) recommend a maximum depth of 15m because of the structural limitation of earthen dikes, Ludwig (2005) suggests a shallow depth of 0.75-2m that is similar to ponds existing in NRG.

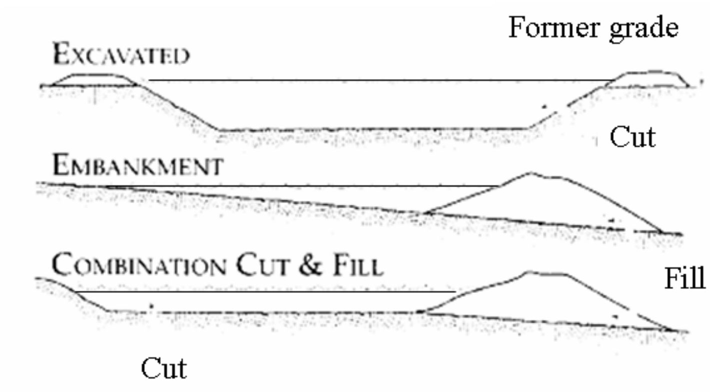

Figure 13 Pond construction classes (Ludwig, 2005)

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[5] Art Ludwig (2005) suggests that the rain harvest be lined with native clay soil or a sandy soil sealed with bentonite clay at least 2mm thick to prevent infiltration of the water from the storage basin.

4.3.2 Evaporative Losses in Storage Basins

High evaporative water losses cause many dugouts to be seasonal. To curb evaporative losses, during a drought in Southern Ghana, European missionaries built large, partially submerged or buried concrete storage tanks in the Afram Plains. According to Ayibotele et al. 1985 cited by Gyau-Boakye (2001), some private houses, public buildings, schools, and hospitals began to build underground cisterns as an alternative to open storage ponds. Water was retreated through hand pumps. Because such cisterns, if built out of reinforced structures can be expensive, ferrocement alternatives were also designed. Unfortunately, most of these structures have fallen into disuse.

4.3.3 Physical Water Quality in Storage Basins

Although dugouts are one of the main sources of drinking water in NRG, ecological design engineer Art Ludwig considers collected runoff to be only suitable for irrigation, flushing salts from the soil, or groundwater recharge (Ludwig, 2005). Like any water body, the water quality of the storage basins is constantly changing physically and microbiologically. In fact, the output water quality can be of considerably higher quality than the runoff water that goes into it. On the other hand, poorly designed storage ponds can degrade water quality because of the effects of heating, bacterial regrowth, leaching, and water age. Solar heating of the water reduces the amount of dissolved gasses, such as oxygen; which can adversely affect the water's taste. Other problems include sunlight catalyzing excessive algal growth, rain flushing animal wastes and agricultural chemicals into the dugout, incubation of bacteria by the sun, leaks, and sediment build-up. If water is stored in dugouts, the WHO warns that cyanobacteria and algae blooms can add color and turbidity to water which can be difficult to remove through filtration (WHO, 2004).

4.3.4 Microbial Contamination in Storage Basins

Without disinfection, there can be vigorous growth of microorganisms in water storage. This in itself is not necessarily a risk unless there is fecal matter introduced to the storage basin. Some bacteria that are attached to particles will be removed from the water through settling or attrition. Other pathogenic microorganisms (enteric) do not survive long in environments like dugouts. In fact, the WHO praises the retention of water in reservoirs because this can reduce the number fecal microorganisms through settling and inactivation (UV disinfection) but mentions how such storage can also can create more opportunities for contamination (WHO, 2004).

4.4 Coagulation

Coagulation, flocculation, clarification (sedimentation), and conventional filtration are the steps for treatment of water with turbidities over 1000 NTU (MWH, 2005). Direct filtration is a pretreatment process which excludes sedimentation so that filtration immediately follows flocculation (Figure 14) (AWWA, 1999). In comparison with conventional filtration, in direct filtration few flocs aggregate and adhere to the filter media and deposited solids. Even so, in developed countries, direct filtration is considered a viable option for surface waters with more stable levels of turbidity less than 15 NTU.

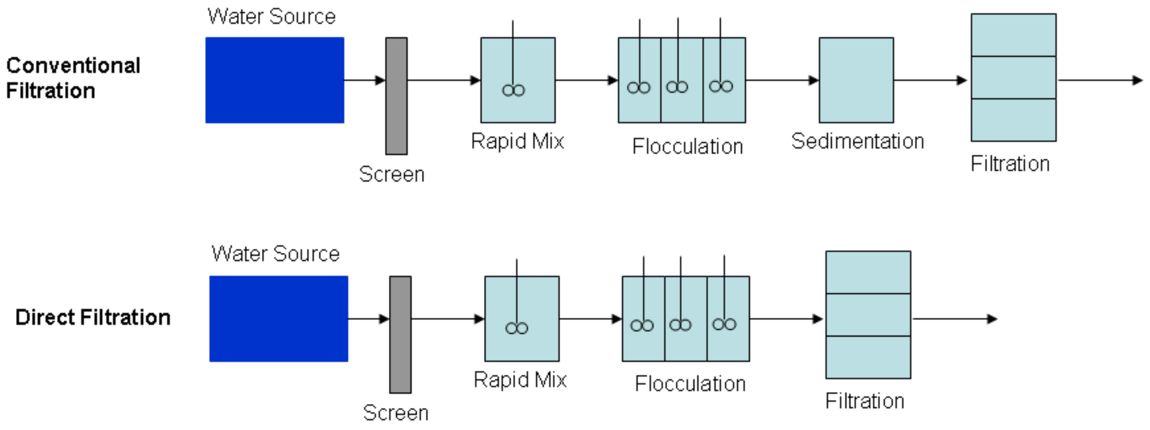

Figure 14 Conventional and direct filtration processes

The risk of using coagulation /flocculation as a pretreatment step in either conventional or direct filtration is that, "improper selection, handling, and feeding of chemicals can be detrimental to water treatment plant performance, having been the bane of many such plants in developing countries." (Okun & Schulz, 1984) In 1971 Neeri, as cited by Okun and Schulz (1984), completed a survey of Indian water treatment plants that presented alarming results: "80 percent of plants were dosing alum in an unscientific and primitive way (by dumping blocks of alum into the raw water channels), because alum equipment was out of order." Alum and iron salts are the most common coagulants. Although Table 7 shows that alum can be effective at reducing raw water turbidity, it is important to conduct jar tests to determine the correct chemical dose specific to the raw water, develop a plan for the system's operation and maintenance, and train capable operators (see Section 12).

Table 7 Efficiency of Alum as a Coagulant (Jahn, 1981 referred to by Schulz and Okun, 1984, p. 67)

Raw Water Turbidity (NTU)	**Alum (mg/l)**	**Residual Turbidity (NTU)**
3200	300	90
1400	100	10
500	30	5
70	10	14

4.5 Roughing Filtration (RF)

4.5.1 Background

In the 1990s, various organizations focused on drinking water supply and sanitation. For example, Water and Sanitation in Developing Countries (SANDEC) and the Centro Inter-Regional de Abastecimiento y Remoción de Agua (CINARA) received funding to promote horizontal roughing filtration (HRF) and standardize design parameters, operation, and maintenance practices (Wegelin, 1996) (Galvis, 2006). Roughing filtration (RF) is a pretreatment technique for turbid water where the water flows through a bed of coarse media such as gravel or burnt clay pottery pieces (Figure 15). Since then, RFs have been implemented in more than 25 countries. Figure 16 illustrates the geographic distribution, by country, of horizontal-flow roughing filters as of 1995.

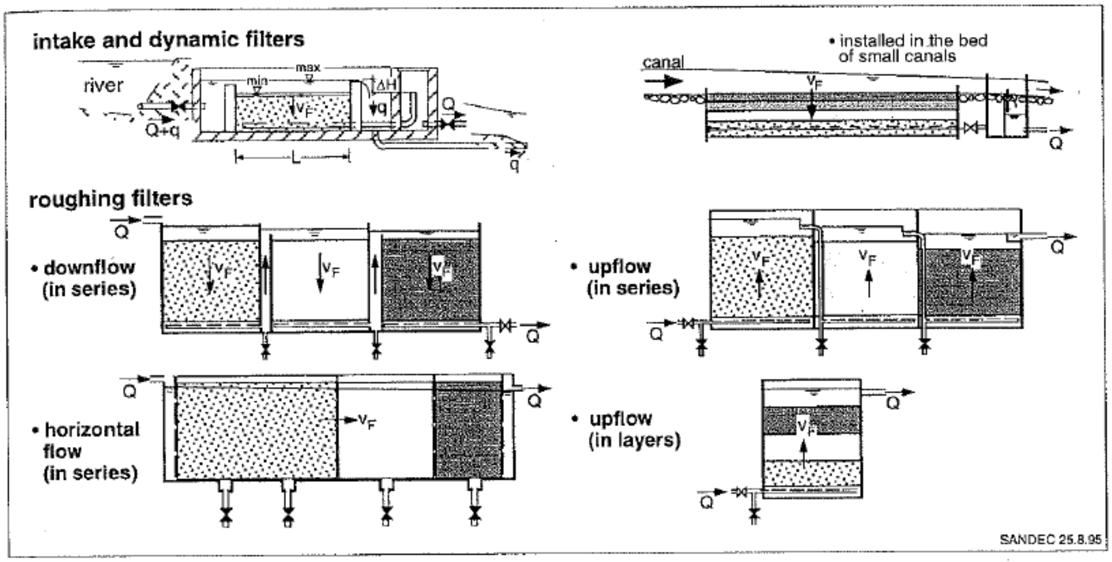

Figure 15 Roughing filter designs (Wegelin, 1996)

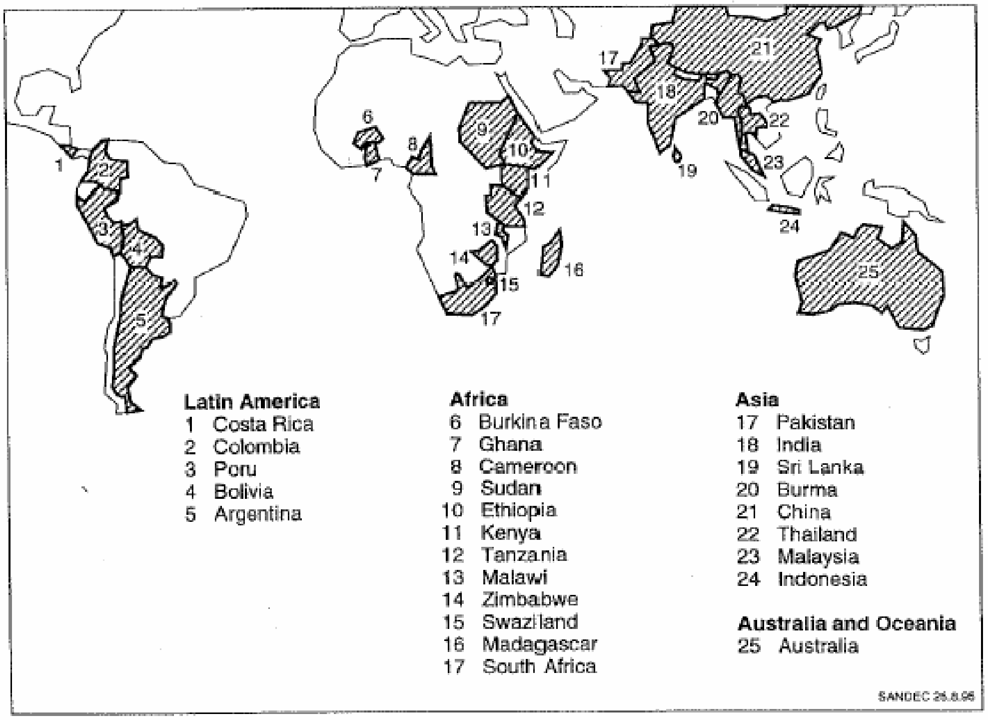

Figure 16 Geographic distribution of horizontal-flow roughing filters in use in 1995 (Wegelin, 1996) http://www.eawag.ch/organisation/abteilungen/sandec/schwerpunkte/ws/documents/surface_water_treatment

The basic attraction of RF pretreatment is that preliminarily removing particles that are larger and more difficult to treat increases the efficiency of subsequent treatment processes such as SSF (Levine et al., 1985). Slow sand filters are comprised of media with 0.15 to 0.35mm diameter while RFs use coarse media greater than 2.0mm diameter. When treating highly turbid water, the benefit of SSF's higher turbidity removal efficiencies is negated by their frequent clogging. To minimize the frequency of RF cleanings and extend the life-span of the RF, average annual raw water turbidities should be between 20 and 150 NTU (Okun and Schlutz, 1996). This pilot study explores whether HRF could be an option in Northern Region Ghana where surface water stored in runoff harvest ponds (dugouts) can seasonally exceed 1000 NTU.

4.5.2 Roughing Filtration Design Parameters

One excellent source excellent source of practical HRF design criteria is Welegin's *Surface Water Treatment by Roughing Filters: A Design, Construction, and Operation Manual* (Wegelin, 1996). Helpful design criteria are also specified in the 23rd WEDC Conference synopsis of how to *Rejuvenate a SSF using HRF Technique* from pilot studies in India (Deshpande & Hingorani, 1997). Experiences from HRF pilot tests in Ethiopia also warrant consideration and offer a complete description of the complete process (Shenkut, 1996). A synopsis of basic RF design criteria recommendations follows:

4.5.2.1 Turbidity Range and Media Sizes

The SANDEC RF Manual design guidelines suggest that for average turbidities above 200 NTU upflow roughing filters in series (UGFS) or a HRF be used (Wegelin, 1996, XII-4). In Northern Region Ghana there is not a record of annual seasonal turbidity variations, however, data collected at two times of the year suggest much higher average dugout turbidities range between dry and rainy season values of 248 NTU and 931 NTU (690 TU) respectively (Foran, 2007; Johnson, 2007). Experts indicate that SSF should have influent turbidities between 20-50 NTU and a filtration rate of 0.13-0.5 m/h (Galvis et al, 1993). With the target of producing a 50 NTU effluent, a RF in NRG needs to remove 80-95% of the influent turbidity.

Table 8 Comparison of Media Filtration Options (Galvis et al, 2006) (Wegelin, 1996)

	Filtration Rate (m/h)	**Media Size (mm)**	**Length or Height (m)**	**Raw Water Turbidities (NTU)**
UGFL (one compartment)	0.3-1.0	25-19 19-13 13-6	0.20-0.30 0.20-0.30 0.20-0.30	50-150 NTU
UGFS (three compartments)	0.3–1.0	25-19 19-13 13-6	0.60-1.0 0.60-1.0 0.60-1.0	50-150 NTU
HRF (three compartments)	0.3-1.5	12-18 8-12 4-8	2-4 1-3 1-2	50-150 NTU and short peaks 500-1000 NTU

Roughing filters' most attractive features are its effective removal of colloidal-size particulates without the addition of coagulant chemicals[6] and its large solid storage capacity at low head loss. Both characteristics can be understood through the transport, adhesion, and transportation mechanisms. Such properties will be further explored with respect to horizontal roughing filters (HRF) because Boller found the particle separation efficiency of horizontal pores in HRF to exceed those of its counterpart, UGFS. (Boller, 1993)

4.5.2.2 Roughing Filtration Particle Removal Mechanisms

Due to the potential presence of small-sized particles in raw surface water, sedimentation and adhesion to media particles, not mechanical straining, are the main filtration process in roughing filters (Okun & Schultz, 1984). As illustrated in Figure 17 and Figure 18, such fine particles do not normally have long enough residence times in a settling basin to overcome a large settling distance. However, the presence of the media decreases the settling distance and allows fine particles to adhere to a sticky bio-film that has formed on the surface of the media.

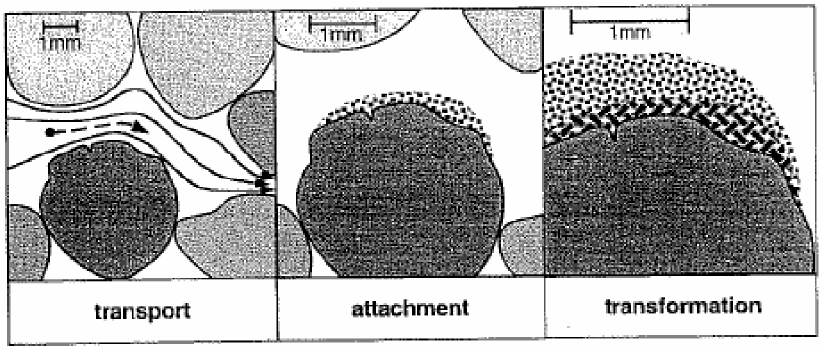

Figure 17 Particle removal mechanisms in HRF (Wegelin, 1996)

Removal of suspended solids in RF requires laminar flow (Galvis et al, 2006). Hydrodynamic forces that move the water through the pore system create patterns of flow retardation and acceleration that have pockets of stagnant water near the media surface allowing particles to settle (Figure 17). A sticky organic film on the surface of the media or in the pores retains the suspended solids by mass-particle attractions through the van der Waals forces and electrostatic forces between charged particles (Wegelin, 1996). Amirtharajah emphasizes how allowing a granular media filter to ripen and form a biofilm strongly influences the quality of water produced (Amirtharajah, 1988).

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[6] The MWH *Water Treatment: Principles and Design* claims that when used in developed countries, roughing filtration often consists of the addition of a coagulant and coarse media filtration through an upflow filter (MWH, 2005, p.874).

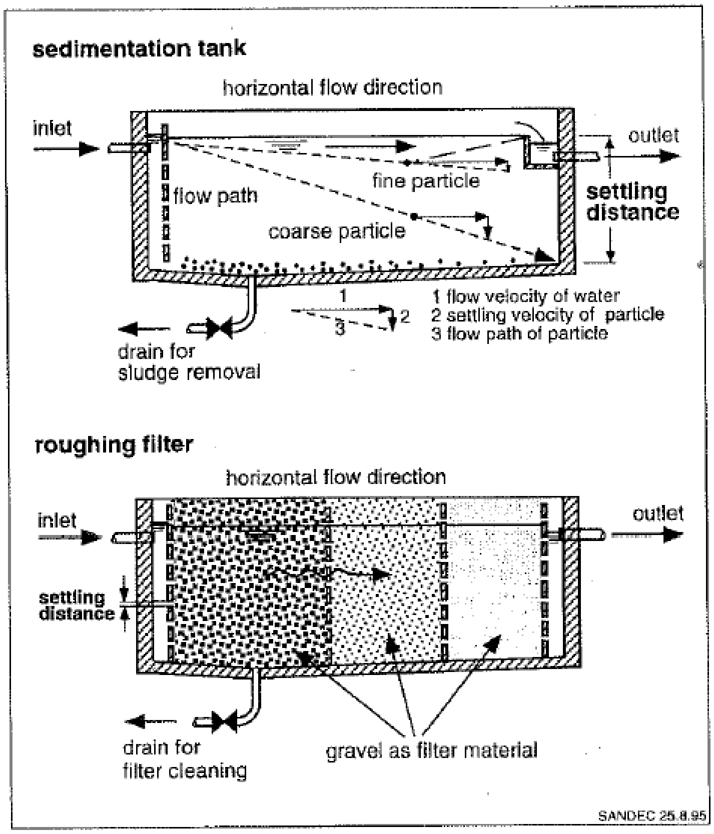

Figure 18 Solids removal in HRF (Wegelin, 1996)

According to the WHO GDWQ (2004), RF can remove 50% of bacteria from raw water and up to 95% if the system is protected from turbidity spikes by dynamic filtration if it is only utilized only when ripened. There is no data for RF removal of viruses or protozoa; however, the protozoan removal is expected to correspond to turbidity removal (WHO, 2004). Some transformation of the suspended solids material may also occur depending on the biological activity of the filter and the type of suspended solids. Such biological transformations can produce smaller particles with higher diffusivities which are ultimately more difficult to remove with RF (Levine, Tchobanoglous, & Asano, 1991).

4.5.2.3 Filtration Velocity

To maximize the amount of particles collected by the HRF, the filtration rate must be low. The filtration rate can be varied slightly; however, studies from SANDEC indicated the filtration rate must be between 0.5 and 2 m/h (Boller, 1993, Wegelin, 1993). The Colombian NGO CINARA, focused on research, development and technology transfer of drinking water supply and sanitation technologies, gives more detailed recommendations for the filtration velocity based on a maximum and average range for turbidity. Unfortunately, in developing countries very little raw water quality data is collected. CINARA suggests a filtration velocity of 0.3 m/h for waters with a maximum and average turbidity of 650 and 84 NTU respectively (CINARA, 1993).

4.5.2.4 Media

Gravel is the commonly used filter media although a few studies have investigated other media (Table 9). One HRF field study completed by the Blue Nile Health Project experimented with broken burnt bricks. Another RF project in Indonesia used *ijuk* palm fiber (Wegelin, 1996). The results from these performance tests showed that exchanging gravel for palm fiber in the first compartment improved the suspended matter removal by 28% (Wegelin, 1996). Completely substituting[7] burnt bricks for gravel decreased the filter performance by 10%. A two-month HRF pilot study conducted at the International Institute of Water and Environmental Engineering ("2IE") using the Loumbila Dam, the main drinking water source for Ouagadougou, showed only average 32% turbidity reduction. A comparison of these 3 HRF project sites and their key design criteria is given in Table 9.

Table 9 HRF Performance Comparison

	Blue Nile Health Project, Sudan (referenced by Wegelin, 1996)		**Plumbon, Indonesia** (Delft University study cited by Wegelin, 1996)		**Ouagadougou, Burkina Faso** International Institute for Water & Environmental Engineering **(**Sylvain, 1989)
Media	broken burnt bricks	gravel	gravel and *ijuk* palm fiber	gravel	quartz gravel
Filtration rate	0.30 m/h		---		1.0 m/h
Filter length and media size (mm)	270 cm, 30-50 85 cm, 15-20 85 cm, 5-10		First compartment filled with fibre; then 16-25 mm gravel	16-25 mm	400 cm, 15-25 150 cm, 5-15
Turbidity (NTU)					
Raw water	40-500		---		5-50
Prefiltered water	5-50		---		4-19
Faecal coliforms (#/100ml)					
Raw water	> 300*	---	---		---
Prefiltered water	< 25*	---	---		---
Mean turbidity reduction	77 %	87 %	67 %	39 %	32 %

* as *E.coli*

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[7] Normally HRF have three segments of decreasing size filled with graded media size ranging from coarse to fine: 10 m long and filtration rate 0.3 – 1.0 m^/m^2*h (Wegelin, 1996).

Although the fine filter media is most effective at particle removal, the coarse media is necessary to allow more space for storage of settleable solids and ease the burden of frequent filter cleanings as seen in Figure 19. With this in mind, numerous studies have investigated the effect different sized medium have on removal of different particle sizes. Ives and Rajapakse from the University College London explored the pretreatment of highly turbid monsoon waters in India with a pebble matrix filtration (Ives & Rajapakse, 1990). Lawler, O'Melia, and Tobiason (1980) investigated the accuracy of models to predict filtration performance based on particle size. Another laboratory-scale HRF at the University of Notre Dame investigated whether the removal of colloidal clays from Cascade Mountain flood waters could be enhanced through the careful choice of media. The chosen limestone media dissolved facilitating sedimentation by destabilization of clay particles through flocculation and sedimentation (Rooklidge, Ketchum, &Burns, 2002).

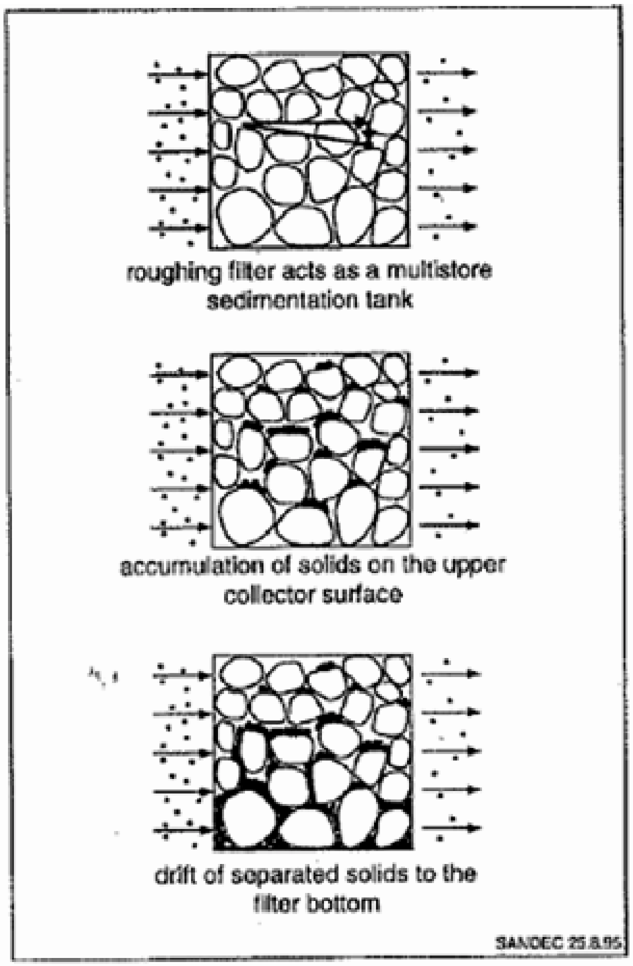

Figure 19 Coarse media storage of settled solids in RF (Wegelin, 1996)

4.5.3 Factors Affecting Roughing Filter Performance

The disadvantage of HRF's low hydraulic load is that the only way to provide sufficient treated water to meet a high drinking water demand would be to build a larger HRF unit (Boller, 1993). The filtration rate (m/h) depends largely on the type of filter, the water's characteristics, and desired turbidity reduction. Variations in the filter media (porosity), each filter medium's proportion, the number of filter fractions, and height and width of filter bed area (m^2) dictate filtration and optimize the removal of suspended matter (Gerardo, 2006). The filter media size (mm) and type (gravel and broken clay) is also an important consideration (Okun & Schulz, 1984). The most influential factor for turbidity removal efficiency is the raw water's particle sizes and distribution (Levine, 1990).

Filter efficiency depends on the concentration of suspended solids. The "1/3 – 2/3" filter theory explains how each layer removes about 1/3 of the particles letting the other 2/3 flow to the next layer (Wegelin, 1996). This continues at each layer. Because there is a greater concentration of particles at the first layer, more particles are removed than in latter layers. Intermittent flow operation can greatly decrease the particle removal efficiency because it is possible that the biofilm around the coarse media might have dried and lost its sticky properties (Galvis, 2006).

Realizing that part of the solution lies in the realm of capacity training and monitoring the Panamerican Health Organization (PAHO) and the Swiss COSUDE created a manual for the operation and maintenance of multi-stage filtration (Galvis et al., 2006). The other piece lies in more fully understanding how biological activities such as algae growth improve or impede particle removal and the behavior colloidal suspensions such as plankton (Boller, 1993).

High sludge storage space can be advantageous in lengthening filter runs but becomes problematic when the filter finally needs to be cleaned. Its buffering capacity to manage fluctuating solid concentrations exists because the large pore spaces allow considerable amounts of solids to be stored at very low head loss (Boller, 1993). Periodic drainage through perforated or corrugated pipe may be able to improve the filter run time between cleanings and needs to be further developed (Boller, 1993). Scraping of the top layer of biofilm on a weekly basis could also improve the filter run time. Fully unpacking the media and cleaning it is one of the biggest drawbacks of the HRF even when the media is readily accessible as it is in HRF.

4.5.4 Evaluating the System

The HRF system is evaluated on headloss, the filtration rate, raw water (influent) and prefilter (effluent) water quality (Wegelin, 1996). Filter performance is evaluated on the following water quality parameters: turbidity, suspended solids, and coliform removal (Galvis, 2006). Particle size characterization can also be done to assess the performance of HRF and SFF and understand how each process alters the particle sizes present and in turn affect treatment performance. CINARA adds that algae, organic color and organic carbon, and true color can also be indicative of raw and prefiltered water quality (Galvis et al, 2006). Temperature, nutrient loads, and dissolved oxygen concentrations should also be monitored as they inhibit and/or reduce the efficiency of treatment process.

5.0 Ghana Background

Ghana lies between latitude 4.5°N and 11.5°N and longitude 3.5°W and 1.5°E (Figure 20). Its climate is controlled by three air masses; the Southwest Monsoon, Northeast Trade Winds (Tropical Continental Air Mass) and Equatorial Easterly. The Southwest Monsoon contributes warm, moist air from the Atlantic Ocean while the Tropical Continental Air Mass (locally known as the *harmattan*) carries hot, dry, and dusty air from the Sahara Desert across Ghana. As these two air masses approach the tropics from either side of the equator, they create a low pressure belt known as the Inter Tropical Convergence Zone (ITCZ). Throughout the year, the ITCZ oscillates in response to the changing angle of the sun and creates a dry and wet season. The Northern Region only experiences one rainfall regime from April/May to October with the rainfall reaching its peak in September (Figure 21). Hardly any rainfall occurs during the 5-month long dry season from November to March. Because the ITCZ passes over the southern region twice, it experiences two rainy seasons. Figure 21 shows the unequal distribution and seasonality of rainfall in Ghana. Not only does the North have much fewer raindays but the monthly rainfalls are substantially lower than the South. As a result, the South is a much more water-rich area while the North is water-poor.

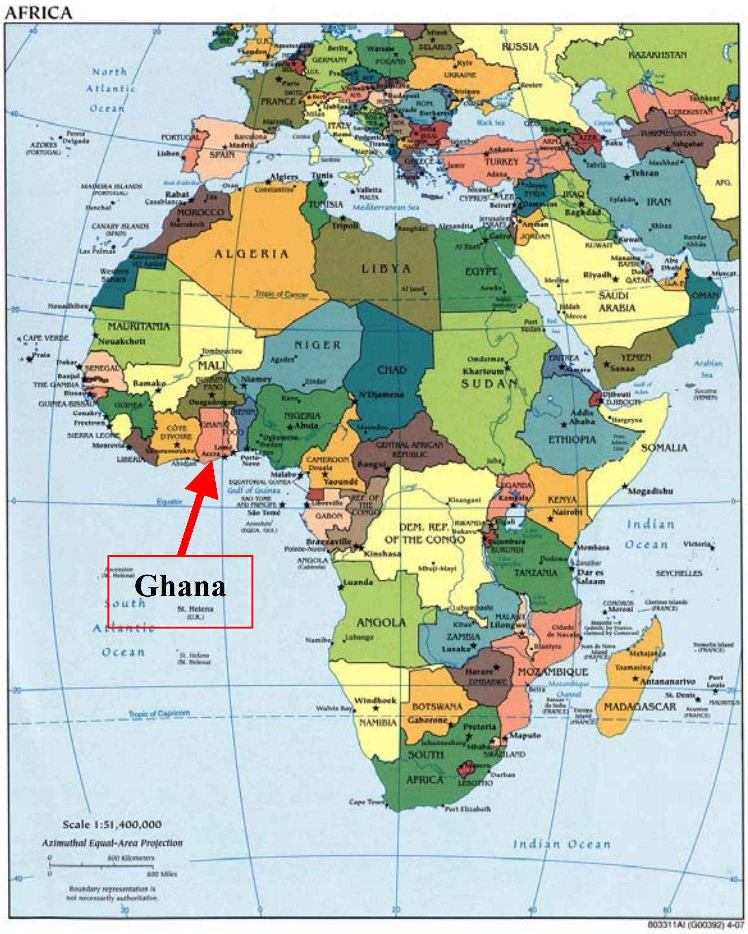

Figure 20 Location of Ghana (http://www.lib.utexas.edu/maps/africa/africa_pol_2007.jpg)

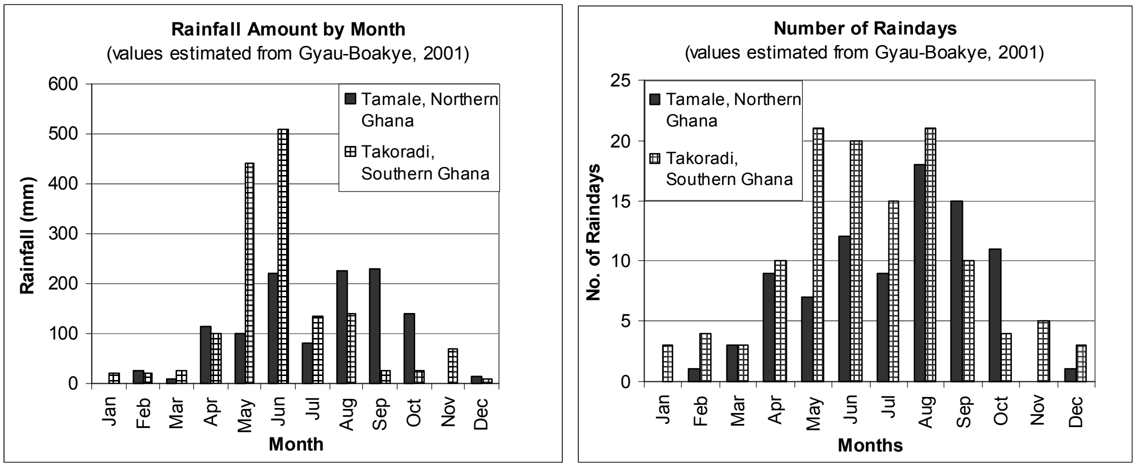

Figure 21 Rainfall chart (left) and number of raindays (right) for Tamale, Northern Ghana and Takoradi, Southern Ghana, 1996 (Gyau-Boakye, 2001)

5.1 History of Water Supply in Ghana

According to the *Millennium Development Goals (MDG) Mid-Term Assessment* in 2004, only 68% of rural water consumers, the most underserved population in Ghana, had access to an improved source (UNICEF, 2004). To reach the MDG 7 for water, an additional 7.3 million rural people need to gain access to improved water sources through an estimated annual investment of $29 million (World Bank, 2004). Increasing urban and rural populations' access to water is a gradual, resource-intensive process. Progress made since British rule and self-rule should be recognized.

The challenge of water supply in Ghana is not a new one. Before colonial rule in 1844, each public or private entity was responsible for developing and managing their water source and supply. In the early 1900s, due to drought, population growth, the gradual migration into more urban areas, and health problems from the contamination of surface waters, the colonial British government claimed responsibility of public water supply in urban and rural areas. Under British rule, the Public Works Department was created to assess urban water supplies. In 1920, the Geological Survey Division was formed to train local authorities in digging wells, protecting the wells with linings, and preventing the contamination of water supplies (Smith, 1969). Water needs in the Northern and Southeastern parts of Ghana became serious enough that the Geological Survey Department was established in 1937. Their mission was to investigate possible new water sources, advise public medical officers, political administrators, and personnel on the proper well digging and maintenance procedures, and to improve sanitary conditions to prevent further pollution of surface water sources.

In the years prior to independence, there continued to be a large need for the development of rural water supplies. Although by 1942, Hydraulic Branch of the Public Works Department had built 252 dams, ponds and wells, the need for potable water in rural areas was so great that in 1944 a separate Department of Rural Water Supply was formed solely to address rural water supply (Smith, 1969). With limited resources, the new department dug wells, built tanks, and trained and supervised local water administrators.

In larger communities, piped systems were sometimes provided from mechanical boreholes. Though this helped, it was not the panacea for Ghana's rural water problems. In the 1950s, concern mounted over the seasonality of groundwater sources. British consultants were invited to advise the Department of Rural Water Supply's work and the potential for groundwater exploitation. Between 1952 and 1959 those working to improve rural water supply partnered with private drilling companies, the Department of Community Development from the Ministry of Social Welfare and Community Development, and the Department of Agriculture[8]. Ayibotele (1969) described the most common technologies that were utilized and continue to be used today: hand-dug wells that sometimes included hand pumps, protective spring boxes, rainfall harvesting from roofs, infiltration galleries, dug-outs, and small dams (as cited by Gyau-Boakye, 2001).

After gaining independence from British rule in 1957[9], the new Ghanaian government reorganized. In 1965 they finally founded the Ghana Water and Sewerage Corporation (GWSC). Act 310 gave the GWSC the responsibility for "the provision, distribution, conservation, and management of water supply development and installation, and for the coordination of all activities related to the water supply industry." (Gyau-Boakye, 2001) Under this organizational structure, a strong effort was made to develop boreholes instead of surface water due to the cost of a potable water supply using surface water being about twice that of groundwater systems according to Ghanaian study by Bannerman (1975) cited by Gyau-Boakye (2001).

According to the Ghana Statistical Service in Accra, before 1984 50% of the rural population depended on surface water such as streams, rivers, lakes, ponds, impoundments from dams, and dug-outs (Gyau-Boakye, 2001). 1984 was an important year because NGOs and the government concentrated their efforts on drilling boreholes and wells in rural communities. Unfortunately borehole drilling was much more successful in the South than the North and resulted in regional inequity with regards to water access (Gyau-Boakye, 2001). The drier Northern Ghana had to satisfy their water demand with limited groundwater and highly turbid, polluted, traditional surface water sources that are often contaminated from the improper disposal of excrement, chemical from agricultural runoff, and the illegal use of DDT (dichloro diethyl tetrachloroethane) for fishing (Gyau-Boakye, 2001).

Figure 22 shows that despite the challenges in financing, implementing, and training the community to manage rural water supply projects, since 1984 there has been improvement in rural population's access to improved water sources. It is unclear whether this change is sustainable and whether the data takes into consideration systems that are broken and have fallen into disuse. Moreover, it should be noted that the improvement of a source does not guarantee the water is microbially or chemically safe but rather focuses on consumers' access to adequate quantities of water rather than its

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[9] In 1957, the Gold Coast was the first African country to achieve its independence from British Rule and became Ghana.

quality[10]. The combination of UNICEF and governmental data show that access to improved water declined by approximately 8% from 1998 to 2000. The World Bank suggests this is "likely due to the incapability of the data and underlines the need for a review of access figures." (World Bank, 2004) However, some of the data could demonstrate a real decline in water access.

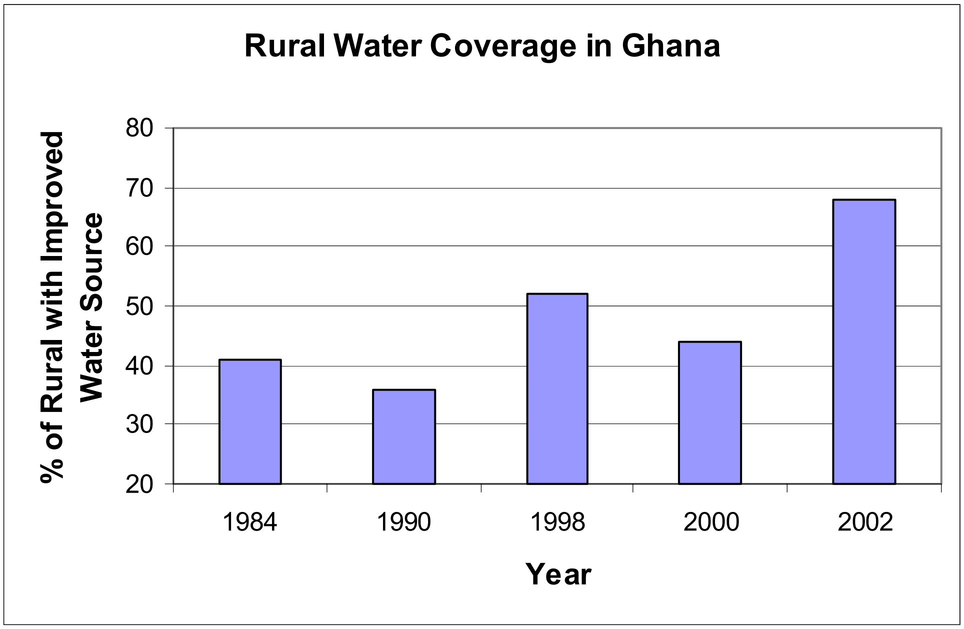

Figure 22 Progress in rural water coverage in Ghana (Gyau-Boakye, 2001; UNICEF, 2004)

Many in Northern Ghana still lack access to improved water sources. Water quantity, source reliability, and the high cost of source improvement projects are challenges that continue to be a barrier to improving water access in Northern Ghana. Figure 23 illustrates that there is a tremendous need to improve access to water (Murcott, 2007).

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[10] The MDG define improved access to a water supply as having at least 20 liters per person per day available from a source within one kilometer of the household.

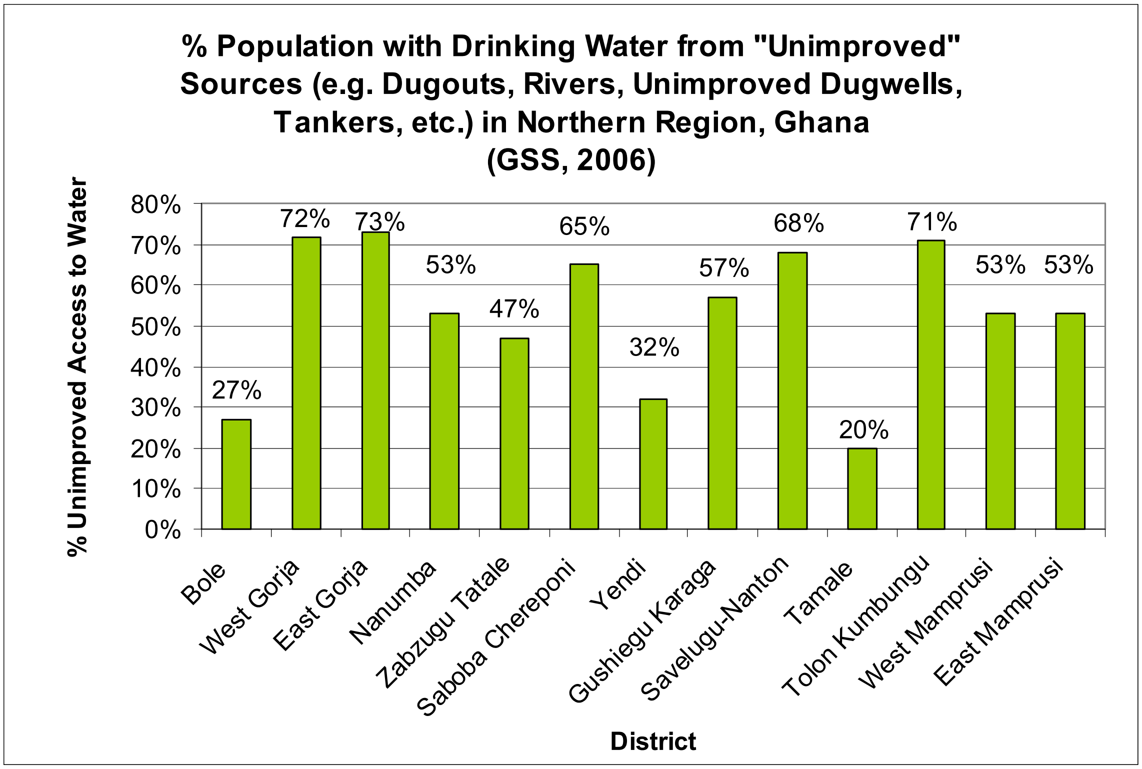

Figure 23 Percent population with drinking water from "unimproved" sources in NRG (GSS, 2006)

5.2 Common Water Sources in Northern Ghana

Common water sources in Northern Ghana include dug-wells, dugouts, ponds, streams, and roof-top rainwater harvesting. Water availability in Northern Ghana is highly seasonal. Streams, hand-dug wells, and dugouts often dry up during the dry season forcing people to travel further in search of water until the aquifers are replenished during the subsequent rainy season.

5.2.1 Boreholes

In areas that have accessible groundwater, boreholes may be the safest, cost-effective long-term solution. Surface water sources can be unreliable because they are transient, seasonal, and at high risk of contamination. On the other hand, drilling rigs and pumps are usually costly, need to be purchased abroad, and require technical expertise. This makes drilling boreholes a challenge in developing countries. Nevertheless, in late 1990s, donor countries such as Canada, Japan, and Germany and a few NGOs such as World Vision International, Oxfam, and UNICEF invested in drilling boreholes in rural communities (Gyau-Boakye, 2001). Like all water treatment technologies, the proper operation, maintenance, and management of boreholes and pumps are essential to sustain a certain treatment standard (see Section 12.0).

It is difficult to locate viable aquifers, especially in Northern Ghana. The hydrogeology of Ghana has two main formations; the Basement Complex of Precambrian crystalline igneous and metamorphic rocks and the Paleozoic consolidated sedimentary formations. The Basement Complex and Voltaian formations are fairly impermeable and therefore do not store groundwater well though fracturing and weathering allow for some aquifer development. Some success was made when joints and cracks were found using reports, topographic maps, geological and structural maps, survey of existing boreholes and water sources, and talking with community members. In the North, baobab trees, a cluster of big trees or an ant hill can indicate that the water table is closer to the ground level. In other regions of Ghana, borehole drilling was successful in valleys or low areas; however, flat topography inhibits this technique around Tamale. To complicate the situation, dropping water levels in the northern, semi-arid region have sometimes dropped up to 5 meters according to Quist et al, 1988 (as cited by Gyau-Boakye, 2001).

5.2.2 Hand-dug Wells

Hand-dug wells are an inexpensive way to access shallow groundwater. Locals can be trained to construct them. There is a great opportunity to further train knowledgeable locals to facilitate community participation so that they are part of the planning, implementation, and management of such projects. Use of an infiltration gallery can reduce the turbidity and general water quality. However, hand-dug wells are limited to areas with accessible groundwater. Most areas in Northern Ghana are not suitable for hand-dug wells. Fifty-four percent of the Ghana has crystalline rocks that make is difficult to dig wells. It is too hard to hand dig below the water table so these wells dry up seasonally. In addition, if they are not correctly capped and sealed with a hand pump added, they can be easily polluted by animals, used domestic gray-water, and water runoff. According to WHO guidelines, hand-dug wells should be located uphill or at least 50 feet (about 15 meters) away from latrines, garbage dumps, and polluted groundwater (as cited by Gyau-Boakye, 2001).

5.2.3 Dugouts/Dams

Dugouts are traditional, earthen basins that catch and store rainwater and interstitial stream flows for long periods of time (see Section 4.3 Earthen Water Storage Basin). Water stored in these runoff harvest ponds is not suggested for potable uses (Ludwig, 2005). However, in the arid areas of Northern Region Ghana and other parts of West Africa where there is limited access to groundwater sources, many communities have few alternative water supplies. These manmade, earthen storage basins are common in rural and urban communities in Northern Ghana where they provide highly turbid surface water to communities with otherwise very limited access to water. In the rural districts of Tolon and Savelugu, over 50% of water sources used by households are dugouts (Figure 24).

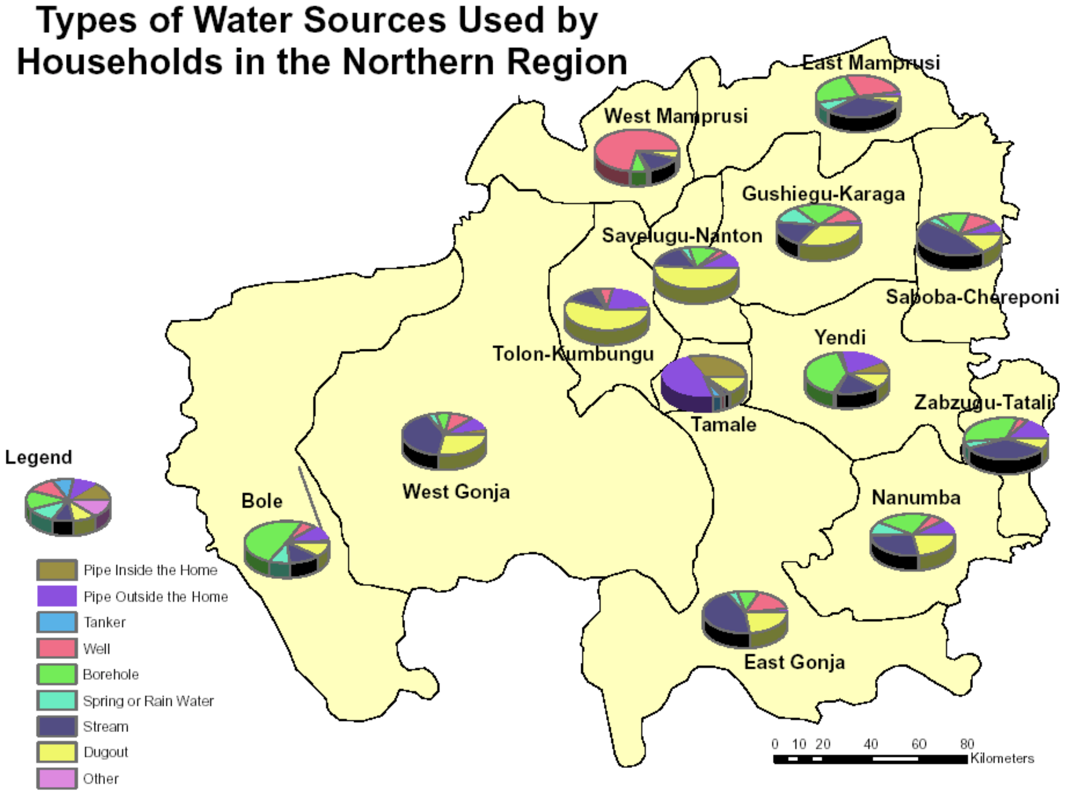

Figure 24 Northern Ghana household water sources (GSS, 2003)

Until all of the dugout water sources in Northern Ghana are identified, protected, and treated, water quality problems will persist at the community and household level. Although a preliminary inventory of dugout location in Northern Region Ghana was completed by Johnson and Doyle (2007), little is still known about the quantity, availability, and quality of dugout water. Only recently has the precise impact the dugouts have on the bacteriological and physical water quality begun to be characterized (Murcott, Doyle, Foran, Johnson, & Yazdani, 2007). In this study physical water quality tests were conducted to characterize the physical water quality of the Gbrumani, Kpanvo, Kunyvilla, and Ghanasco Dams in the Tamale area of Northern Ghana (see Section 7.0).

MIT Master of Engineering and Harvard Master of Public Health students Johnson (2007) and Foran (2008) were the first to compile water quality data on dugouts in and around Tamale. From Table 10, it is evident that dugouts' high average concentrations of *E.coli* and turbidities greatly exceed the WHO DWQG and are a serious water quality problem that needs a solution. SSF could be a highly effective treatment option for removing 99-99.99% of microorganisms; however, the average dry season turbidity of 248 NTU (Johnson, 2007) and average rainy season turbidity[11] of 931 NTU (690 TU) (Foran, 2007) exceed the recommended 20-50 NTU for SSF (Wegelin, 1996). Therefore, a turbidity removal pretreatment step, such as HRF, is necessary prior to SSF.

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[11] For a description of the relationship between NTU and TU see Appendix D: Relationship between Nephelometric Turbidity Units (NTU) and Turbidity Units (TU).

Table 10 Results from Raw Dugout Samples in Tamale and Savelugu Districts

	Dry Season (Johnson, 2007)	**Rainy Season (Foran, 2007)**
Average *E.coli* (CFU/100 mL)	779	438
Average Total Coliform (CFU/100 mL)	26,357	12,797
Average Turbidity	**248 NTU**	**931 NTU** [12]

Given the high incidence of diarrhea in children under five in the Northern Region[13], improving dugout design in order to reduce the turbidity and make the dugout water more treatable by SSF could help to prevent cases of diarrheal disease. Dugout construction and maintenance also affects the incidence of malaria because stagnant water can be breeding areas for the *Anopheles* mosquitoes. Some potential dugout improvements could be to (Ludwig, 2005):

- Pick a cleaner a source;
- Keep water cool to slow bacterial growth;
- Raise the pH of the water by adding lime;
- Prevent leaks through improved pond-floor lining;
- Place *Gambusia* (mosquito fish) in dugout water to feed on *Anopheles* larva;
- Build natural vegetative barriers to prevent runoff-carried particles from entering the dugout.

When dugouts dry up, many communities are forced to purchase water from water vendors which can be very costly as seen in Table 11 (Okiago, 2007).

Table 11 Cost of Vended Water in Tamale Area (Okiago, 2007)

Water Source	**Quantity (liters)**	**Price (US$)**	**Price per Liter**
Vended	20 L	$0.17	$0.0085
Vended	200 L	$0.94	$0.0047
Tanked water via a third party	1000 L	$3.00	$0.0030
	Average		**$0.0054**

Alternatively, people are forced to walk longer distances to collect water.

5.3 Water Quality of Dugout Water in Northern Ghana

Long-term water quality data is often lacking because funding is unavailable, workers are untrained and inexperienced with the testing methods, and the correct laboratory and field equipment are inaccessible. Despite these challenges, the WHO GDWQ and engineers working in developing countries emphasize the importance of matching the correct particle removal design with the problem (WHO, 2004) (Wegelin, 1996). According to

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[12] Originally these rainy season measurements were done in TU with a turbidity tube. The average rainy season turbidity is 690 TU. This value was converted using the TU-NTU correlation described in Appendix D.

[13] According to the Ghana Statistical Services' data from 2003, 15.3% of children under five years of age have diarrhea.

Howard (2003), communities need to be part of the water quality collection, testing, and analysis of results or at least be informed of results if outside entities complete them. It is particularly important that they learn which water sources are most contaminated, because this might cause positive behavioral change.

Prior to the general hydrogeological and water supply summary done by Gyau-Boakye (2001), very few technical studies explored the quantity and accessibility of Ghana's drinking water supplies. In 1968, Lartey and Smith (1968) published a report investigating water issues from an economic and health standpoint with an emphasis on the impact population growth has on rural water supplies (see Section 5.0). Smith's rudimentary report in 1969 touched on urban water supply development, potential hydropower development projects, and river basin management but lacked data and conclusive findings especially about drinking water sources and their quality. Ofosu's report (2006) on the *Hydrogeology of the Voltaian Formation of the Northern Region Ghana* explores the limitation of groundwater resources. No report offers in-depth information about surface water problems in the Northern and/or Upper East and Upper West Regions where agriculture, livestock breeding, and human development is greatly limited by highly turbid, seasonal surface water supplies. Neither records of turbidity nor chemical composition were found for dugouts in NRG.

Although, in this study, the community was not part of the water quality surveillance, if a dugout water quality study were expanded, community participation and decision-making would be a key piece of the study. When trying to understand the quality of a water source, the WHO suggests data be gathered about the following subjects, in addition to the actual water quality parameter measurements taken (WHO, 1996, Table 4.1):

- Catchments;
- Geology and hydrology;
- Meteorology and weather patterns;
- General catchment and river health;
- Wildlife;
- Competing water uses;
- Nature and intensity of development and land use;
- Other activities in the catchment that potentially release contaminants into source water;
- Planned future activities.

Currently, most of these steps do not occur in NRG.

5.3.1 Waterborne and Water-related Disease

Many waterborne diseases come from fecal pollution from human and animal sources that wash into surface water. Defecation nearby or the location of a latrine uphill puts the water body at higher risk of fecal contamination with waterborne diseases such as diarrhea, typhoid, infectious hepatitis and cholera and water-related such as Guinea worm and bilharzias. The incidence of such diseases is very high in communities that drink untreated surface water. The morbidity of such diseases can have serious economic implications for people who are infected and find themselves unable to work or take care of their family. This is particularly true for rural subsistent farmers whose harvests may decrease because they were unable to work during an important point of the crop's growing season.

5.3.1.1 Guinea Worm

*Dracunculus medinensis*is, also known as Guinea worm disease, is an ancient parasitic disease that was once widespread and is still endemic in Ghana and Sudan. It mainly affects poor populations in remote, resource-limited communities in Africa where there is inadequate access to potable water, health care, and education. This debilitating helminthes disease was called the "empty granary" disease in Mali because it left subsistent farmers incapacitated for such long periods of time that they lost part or all of their harvest. In 1986, it was estimated that 3.2 million people in 20 endemic countries in Africa and Asia were infected and 125 million were at risk of infection[14]. Eradication became a recognized target of the World Heath Assembly in 1991(WHO, 2004). The success of a global eradication campaign is mainly attributed to adequate funding and the strong leadership of the Centers for Disease Control, UN's Children Fund (UNICEF), the WHO, and the Carter Center which persuaded National Ministries of Health, local NGOs, the private sector, village volunteers, and infected individuals to make eradication of this debilitating disease a priority. Despite initial skepticism about the effectiveness of a behavior-based intervention plan, the Guinea Worm Eradication Program has become an example of the possibility of using cost-effective methods of controlling and even eliminating a disease at a national level.

The Guinea worm disease cycle begins when a person drinks contaminated water from a stagnant source that contains copepods[15] capable of transporting the Guinea worm larvae. Inside the human body, the copepods are killed by strong stomach acid and disperse larvae which travel into the small intestine. Sixty to ninety days later the male and female larvae mate. During the next year the female grows to be two to three feet long. Symptoms include a burning sensation in the infected area, fever, and occasionally diarrhea. As the female worm reaches full maturation, she burrows out of the skin in search of a water source where she can lay her larvae. Instinctively, individuals submerge the infected area in cool water to sooth the pain. Unfortunately, the cool water stimulates the blistered skin to rupture and release hundreds of thousands of larvae. There is no vaccine to prevent or medication to treat guinea worm disease, however, simple filtration of contaminated water with a cloth, sand, or ceramic filter will remove the copepods, which are approximately 1 mm in size and visible to the naked eye (Figure 25 and Figure 26).

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[14] The 20 countries where guinea worm disease was endemic are Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Central African Republic, Ethiopia, Ghana, India, Kenya, Mali, Mauritania, Niger, Nigeria, Pakistan, Senegal, Sudan, Togo, Uganda, and Yemen

[15] Copepods small crustaceans, 1-2 mm long, present in the ocean and most freshwater habitats. Pathogens such as the cholera bacteria and guinea worm larva are ingested by the crustaceans. Those who consume contaminated unfiltered water are at risk of ingesting a copepod carrying a pathogen. http://en.wikipedia.org/wiki/Copepod

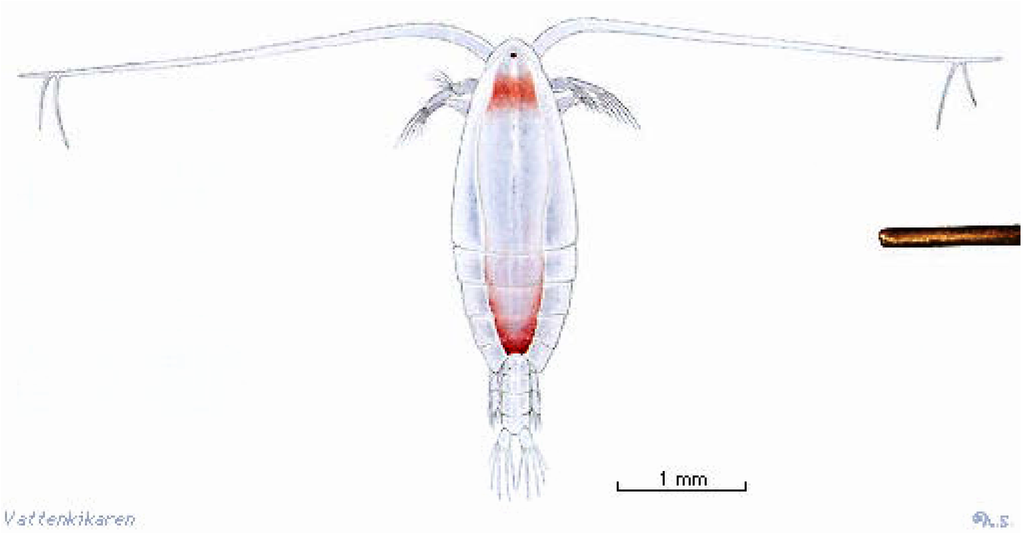

Figure 25 Copepod size in comparison to a magnified hair (http://www.vattenkikaren.gu.se/Fakta/arter/crustace/copepoda/copese.html)

Figure 26 Guinea worm educational poster (left) and Guinea worm cloth filter (right) Kpanvo, Northern Region Ghana

The main burden from the disease arises from debilitating pain and infection that can last 12 to 18 months after the worm's emergence. Although Guinea worm disease impacts all age groups, it is equally devastating to children because they miss educational opportunities and but also to adults who cannot assume the agricultural and household responsibilities which can lead to poverty and food scarcity.

The key factor in eradication of Guinea worm disease is to interrupt the transmission for one year through case identification and treatment, treatment of unsafe sources with Abate® larvicide, case containment, cloth filters, and education campaigns. Reaching remote communities most at risk of Guinea worm disease has proved to be a challenge when the affected communities are poor, illiterate, and difficult to access. The behavior change intervention promotes disease prevention education in remote communities and the improvement of their water treatment and storage. Over the years, the most cost-effective intervention proved to be 200µm monofilament nylon filters and health education and social marketing. In fact in Ghana, studies show an 80% decrease in cases in communities participating in health education and social marketing campaigns, such as US Peace Corps "worm week," the radio, T-shirts, posters, banners, stamps, painted vehicles, and video interventions, versus the 45% reduction in villages without such programs. However, because public education campaigns depend on the voluntary participation of residents and sometimes are not well received by traditional people who have their own indigenous explanations of Guinea worm, many still remain skeptical about their effectiveness. Improvement of communities' water source, though important in the long-term, was difficult to implement on a large scale due to the exorbitant per capita cost of more than $40/per person plus maintenance costs.

As a result of these coordinated efforts, the world saw a 99% drop in Guinea worm prevalence. In 2005, the majority of remaining cases were in Sudan (5569 cases) and Ghana (3981 cases). An average of 3.5 million cases has been prevented annually (Levine, 2007). This sums to 63 million cases of Guinea worm disease prevented since 1987. According to economic analysis, between 1987 and 1998, the global campaign received $87.5 million from governments and private sector donors. One notable donor in 2000 was the Bill & Melinda Gates Foundation for $28.5 million. The cost per case prevented ranged from US$5-8. This success illustrates the power of coordinating across agencies and governments to achieve a specific disease burden reduction (Levine, 2007).

Though successful, the campaign's work is not yet complete. In Sudan, progress is stalled by civil unrest. A political solution is required before any systematic intervention can be implemented. As the first African endemic country to implement a national Guinea worm disease prevention program in 1986, Ghana should have seen much more progress especially because they created a successful village volunteers' monthly reporting system that trains community health promoters to reach remote areas and allows data in rural areas to be collected. Because of its voluntary nature, it is questionable whether such a program will be effectively managed long enough to eradicate the disease. Such volunteer programs require continued organizational attention and resources to distribute, replace, and monitor the use of the nylon filters, identify and treat cases, contain cases, apply Abate® to infested dugouts, and run educational campaigns.

Other interventions focused more on improve the water source because until the supplied water is free from contamination, health problems at the household level will persist. When Guinea worm was endemic in places like Mafi Kumase in the Volta Region of Southern Ghana, horizontal roughing filtration and slow sand filtration were successfully implemented as community interventions to remove copepods from the contaminated dugout water. For more information see Section 11.0.

6.0 Methods Used for Water Quality Testing

The water quality tests focused on physical water properties (i.e. turbidity, filtrability, settleable solids, suspension stability, and sequential filtration) and microbial contamination.

6.1 Sample Collection

The author collected samples from four dams (including Ghanasco Dam) and the pilot HRF while it was running from January 13, 2008 to January 25, 2008. After the MIT team's departure, Carl Allen (industrial engineer and Peace Corps Ghana Math Teacher and Peace Corps Volunteer Leader) continued to take samples from the Ghanasco Dam and pilot HRF from January 26, 2008 until February 28, 2008.

6.1.1 Dugout Sampling

The samples for the physical water quality tests were taken at the shore of the dam without entering the water. A plastic bucket or clean, reused Volta® plastic water bottle was dipped just under the surface and allowed to fill with surface water. The samples were taken from a place frequently used for water collection by the local population. On a given day the dugout turbidity could vary based on depth and location of sampling site. Most of this variation was probably caused by mixing processes in the water caused by wind advection, animals drinking from the dugout, and people disturbing the water and underlying mud sediments when collecting water. Nonetheless, the samples were representative of the type of water being used in surrounding households. Sample bottles and buckets were rinsed three times with pressurized tap water and reused (Figure 27).

Figure 27 Location of Ghanasco Dam water collection (left) and Volta® plastic sample bottles (right)
Photo Credit: Carl Allen (left)

6.1.2 Pilot HRF Sampling

6.1.2.1 Tank Sampling

To collect settled water from the tanks, a plastic liter beaker was lowered below the surface of the G and P tank water. A turbidity tube was used and the turbidity was recorded in TU. Then the tank was mixed vigorously and samples were taken again from below the surface. Once again, the turbidity was measured with a turbidity tube and recorded in turbidity units (TU). Back at the lab, the samples' turbidity was measured in nephelometric turbidity units (NTU) using the turbidimeter.

6.1.3.2 Effluent Sampling

Because of the HRF's slow flow rate, a method had to be devised to collect the effluent water. A narrow nail-size hole was burrowed into the bottom lip of the final tube. A small strand of dental floss was tied through the hole and allowed to hang down so that effluent water would flow or drip in a stream into the collection vessel. The end of the tube was covered Saran Wrap® to prevent dust from accumulating on the final media and altering the effluent turbidity (Figure 28). The samples were carried back to the TSO in reused plastic water bottles (Figure 29).

At times, the flow rate needed to be readjusted by either opening or closing the valve. Although this was done carefully before taking samples from the effluents of the G, D, and P tubes to not disturb biofilm formation on the media, sometimes the valve was opened too far and for a few seconds the flow rate was too high. Samples were taken from the pilot HRF effluents daily.

Samples were also collected in a 1 L plastic beaker from the Mafi Kumasi HRF in the Volta Region of Southern Ghana to test the filtrability of the system's influent and effluent water.

Figure 28 Collection of HRF effluent
Photo Credit: Carl Allen

Figure 29 Pilot HRF samples collected by PCVL Carl Allen in February (February 28, 2008)
Photo Credit: Carl Allen

6.1.4 Microbial Sampling

Microbial samples from the dam and the tanks were collected by carefully dipping the 100 ml Whirlpack® bag below the water surface. Microbial samples from the pilot HRF system were collected directly from the effluent tubes in Whirlpack® bags. If it was found that the filter valve was clogged and had stopped the flow of water, then the flow rate was readjusted and allowed to flow for 3-5 minutes before sampling. Contact of the bag with the dental floss used to guide flow was minimized but occurred. All the samples were stored in a cooler with ice packs and processed within six hours of their collection. These results are the fruits of a collaborative effort. Ghana Rural and Sanitation Peace Corps Volunteer, Mike Dreyfuss, and Stanford Environmental Engineering Ph.D. Candidate Sophie Walewijk, collected and analyzed these samples.

6.1.5 Ghanasco Dam Surface Soil Sample

The soil sample was collected from the surface between the dugout and the pilot HRF at Ghanasco Dam so that it would be representative of particles that rain could wash into the dugout. The sample was stored in double Ziploc® bags at room temperature.

6.2 Physical Water Quality of Dams and Pilot HRF

The appendix Simple Methods for Water Quality Analysis from SANDEC's *Surface Water Treatment by Rouging Filters: A Design, Construction, and Operation Manual* was used to assess both the physical particle properties of several dams in the Tamale area and the performance of the pilot HRF at Ghanasco Dugout near Vittin Estates, Tamale. Wegelin developed these simple, practical, field methods that use durable, inexpensive equipment to make water quality monitoring and filter performance possible in low-income communities (Wegelin, 1996). SANDEC developed a field test kit but it has not been widely marketed or disseminated. These tests do not require any special chemical or electricity/energy supply. They can be done in remote areas and the test equipment can be copied by local craftmens who work with plastics (Wegelin, 1996).

Suspended solids concentrations are very difficult to measure in the field because they require an analytic balance and other expensive lab supplies and equipment. Although the following tests are much less expensive than using complicated Coulter Counters and scattering light analysis, purchasing the necessary polycarbonate capillarpore membranes paper filters in developing countries can also prove to be either difficult, impossible, and/or prohibitively expensive. For the case of this study, the following tests will indicate the relative presence of suspended solids in a water sample and the suspension's solid matter stability.

Figure 30 Laboratory space at the Peace Corps TSO

6.2.1 Turbidity Analysis

Turbidity and suspended solids[16] concentration are the key parameters used to measure the HRF's effectiveness in improving physical water quality. In the field, either a turbidity tube[17] (sold by DelAqua®) or the more accurate, battery-powered turbidimeter can be used. The turbidity tube measures in turbidity units (TU) and the turbidimeter in nephelometric turbidity units (NTU)[18]. In comparison with the turbidimeter, the turbidity tube readings are dependent on visual observation which varies from individual to individual. The correlation between TU to NTU was analyzed using field and laboratory data and can be found in Appendix D.

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[16] Suspended solids are not to be confused with turbidity. While turbidity is a measurement of the cloudiness or haziness of water due to particles blocking light as it tries to pass through the sample, suspended solids are the measure of the actual particle mass per mass of water.

[17] The DelAqua® turbidity tube measures: 25.5cm long, outer diameter of 2.8cm, and inner diameter 2.3cm.

[18] Particle sizes smaller than 1.0μm are not measured accurately by suspended solids or optical techniques such as turbidity. Size distribution analyses are better evaluations of performance (Levine et al, 1985).

Figure 31 Turbidity tube (left), Hach® turbidimeter (center), and Hach® turbidity vials (right)

The turbidity tube is a clear narrow plastic test tube with markings from 5 TU to 2000 TU. There is a bulls-eye marked on the bottom of the test tube. Because of the influence light intensity has on the turbidity reading, an effort was made to take turbidity reading in the same sort of light conditions using artificial or indirect sunlight. Turbidity of the G and P tanks, and G, D, and P tubes were taken in the field with the turbidity tube and then with the Hach® 2100 P portable, digital turbidimeter in the TSO lab (Figure 31).

Turbidity Tube Procedure

1. Shake the sample well.
2. Fill the tube with water slowly until the bulls-eye is no longer visible.
3. Record the turbidity value and empty the tube.
4. Flush the tube three times with water. (In the field, the tube was flushed with the cleanest water available, usually water from the neighboring biosand experiment.)

Turbidimeter Procedure

1. Shake the sample well.
2. Pour 30mL of the well-mixed sample into the glass, turbidity vile (Figure 31).
3. Wipe the side of the glass vile with the felt cloth.
4. Turn the turbidimeter on and place the vile in the turbidimeter.
5. Measure and record the turbidity.
6. Remove the vile and empty and rinsed it three times with clean water.

6.2.2 Filtrability

The filterability test is a low-cost substitution for suspended solids but has the drawback that it only yields relative values of solid matter removal when the influent and effluent of a filter are compared.

Filtrability Materials

- Filter set (250mL cylinder, 250mL filter support, filter disk)
- 1.5µm polycarbonate capillarpore membrane, 47mm diameter filter paper (FT-3-1101-047 from Hach®)
- 100mL graduated cylinder
- Stopwatch

Procedure

1. Connect a 250mL measuring cylinder to the filter support.
2. Saturate the porous filter disk with water.
3. Place and press a 1.5µm filter paper with medium filterability on the filter support carefully not to trap any air bubbles beneath the filter paper.
4. Screw the vessel on to the filter support (Figure 32).
5. Poor 200mL of the sample in the vessel and start a stop watch.
6. Record the volume of filtered water after 1, 2, and 3 minutes.
7. Remove the filtered water and flush the apparatus with high-pressure tap water.

Because of time, a limited supply, and the expense of filter papers, the filterability of each sample was only tested once.

Figure 32 Filter setup (left), Imhoff Cone (right)

6.2.3 Settling

6.2.3.1 Solids Settleability

Imhoff cones are usually used to test wastewater solids removal by sedimentation and settling, however, they can also be useful in for raw water with a high concentration of settleable solids. The test basically shows the volume of settleable solids that could be removed if there were no pretreatment and water was stored in a water reservoir where sedimentation occurs. Dugout water and HRF tanks and tubes were tested.

Solids Settleability Materials

- 1L Imhoff cone
- 1L beaker
- Saran wrap®

Procedure

1. Tie the Imhoff cone to a post in the vertical position (Figure 32).
2. Pour 1L of water into the cone slowly.
3. Cover the Imhoff cone with Saran wrap®.
4. Record the volume of settleable solids after 15 minutes, 30 minutes, 1, 2, 4, 8, and 24 hours.
5. Remove the bottom screw from the Imhoff cone, scrub the cone, and flush it with high-pressure tap water three times.

6.2.3.2 Suspension Stability

This test is similar to the solids settleability test described above in Section 6.2.3.1 Solids Settleability however instead of focusing on the volume of particles that settle, this test records the amount of turbidity remaining in the water, i.e. the stability of the suspension. Together these two tests complement each other and are a good indication of the settling characteristics of suspended matter present in the dugout water (Wegelin, 1996).

Suspension Stability Materials

- 1.5L Volta® plastic drinking water bottles
- 1L beaker
- Turkey baster
- Saran wrap®
- Hach® 2100 P portable, digital turbidimeter

Procedure

1. Cut off the tops of 1.5L Volta® plastic drinking water bottles and use these containers for the suspension stability tests.
2. Place the plastic bottles in a room without windows.
3. Fill the bottles with 1L of water and cover them with Saran wrap®.
4. Remove 25mL samples from each beaker with a turkey baster carefully as to not disturb the water at 0, 15, 20, 60, 90, 120 minutes and after 4, 8, 24, 32, and 50 hours.
5. Squirt the water sample into a 25mL glass vile and measure the turbidity with the digital turbidimeter.
6. Flush the glass vials and turkey baster three times with clean water.

Figure 33 Settling stability test on dam water at the TSO (January 21, 2008)

6.2.4 Sequential Filtration

Sequential filtration is similar to serial filtration in wastewater treatment which reliably models the particle size distribution of particles larger than 0.1µm (Levine et al., 1985). SANDEC recommends a range of 47 mm diameter, polycarbonate capillarpore membranes be used for sequential filtration (Wegelin, 1996).

Sequential Filtration Materials

- Filter set (250mL cylinder, 250mL filter support, filter disk)
- Hach® 2100 P portable digital turbidimeter
- 1µm, 8-12µm, and 20-30µm polycarbonate capillarpore membrane, 47mm diameter filter paper (ZB921 from Schleicher and Scull)

Procedure

1. Place the 20-30µm filter paper on the filter holder.
2. Measure and pour 25mL of the sample into the filter vessel.
3. Allow it to filter and collect 10mL of the filtrate into the glass vile.
4. Measure the filtrate's turbidity using the turbidimeter.
5. Repeated this process for the 8-12µm and 1µm filter papers.

6.3 Microbial Testing

The microbial samples were tested using membrane filtration to quantify the number of total coliform colony forming units (CFUs) and *E. coli*[19] bacteria CFUs are present in a 100mL water sample. A red colony indicates one *E. coli* bacteria in the sample. A blue colony indicates one bacteria of some other coliform. These tests were performed by Sophie Walewijk, Stanford University, Environmental Engineering, Ph.D. Candidate and

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[19] *E. coli* is an indicator type of enteric bacteria whose presence suggests that pathogenic microorganisms could be present.

Mike Dreyfuss, Peace Corps Ghana, Rural Health and Sanitation Volunteer at the PHW laboratory. An adapted version of Millapore's *Water Microbiology: Laboratory and Field Procedures* was used.

Membrane Filtration Materials

- Isopropyl alcohol
- Millapore® portable unit with filter holder and pump (Millipore, XX63 001 50)
- m-ColiBlue24 media
- 47mm absorbent pad
- 0.45µm, 47mm, white gridded filter pad
- Recyclable metal Petri dishes
- Candle
- Matches
- Tweezers
- Magnifying glass
- Sterile bottled water
- Microfilter paper
- Automatic pipette
- Metal cup
- Methanol
- Two 100mL graduated cylinders
- Incubator (Millipore Environmental Incubator (Portable), XX 63 200 00)
- Aluminum foil
- Small and large lids

Procedure

1. Sterilize all laboratory surfaces with isopropyl alcohol.
2. Sterilize the filter holder.
    a. Wet the absorbent ring wick with methanol.
    b. Ignite the ring.
    c. While the methanol is still burning, cap the filter with the lid.
    d. Let the filter stand for 20 minutes.
3. Assemble the sterile filter.
    a. Rinse the upper basin with sterile bottled water.
    b. Detach the upper basin.
    c. Place a microfilter paper on the filter pedestal's mesh screen.
    d. Attach the upper basin.
4. Prepare the dilutions.
5. Filter the diluted sample.
    a. Add the diluted sample to the upper basin.
    b. Attach the pump to the filter and pump 3-5 times or until most of the sample passes through the filter. (If the sample still does not pass through the filter, pump continuously.)

    c. When most of the sample has passed through the filter, wash the upper basin with sterile water.
6. Prepare the sterile Petri dish.
    a. Place the paper filter in the center of the sterile Petri dish. (If metal Petri dishes are not available, a small sterile jar lid is covered with a larger jar lid like a clam shell or is covered with sterile Aluminum foil.)
    b. Add one ampule of mColiBlue24 media to the dish in an outward spiral of drops covering the whole paper.
    c. Decant the excess media.
7. Incubate the Petri dish.
    a. Place the metal Petri dish upside down for 24 hours. (If using jar lids, they are incubated right-side-up.)
    b. Remove the Petri dishes from the incubator after 24 hours.
    c. Read samples under a magnified glass.

6.4 Arsenic and Lead Tests

Kendra Johnson and a group of MIT undergraduate students in Civil and Environmental Engineering sent a sample of the Ghanasco Dam soil to be tested for arsenic and lead to the University of British Columbia, Department of Earth & Ocean Sciences[20]. They used a Philips PW2400 wavelength-dispersive sequential automatic spectrometer to analyze the sample according to the methodology described in Calvert, Cousens, & Soons (1985).

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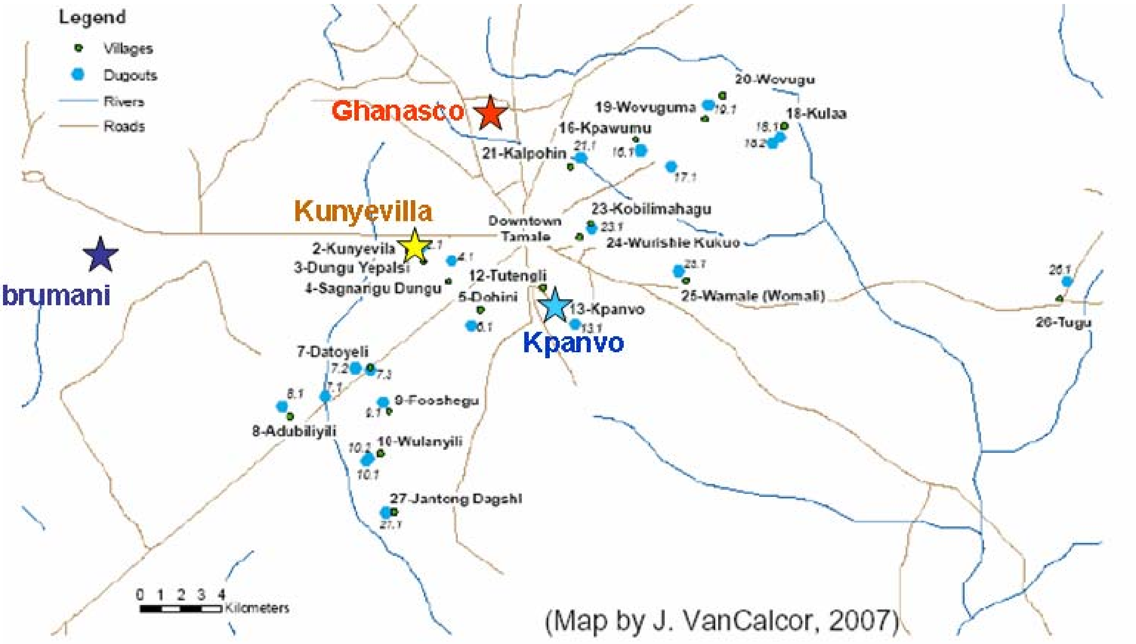
[20] University of British Columbia
Department of Earth and Ocean Sciences
Oceanography
1470 - 6270 University Blvd
Vancouver, BC
Canada V6T 1Z4
Tel: 604-822-2796
Fax: 604-822-6091

7.0 Physical Characteristics of Dugout Water

Comprehensive low-cost, field procedures developed by Wegelin from SANDEC in the *Surface Water Treatment by Roughing Filters: A Design, Construction, and Operation Manual* (1996) guided the methodology for studying the physical water characteristics of dams in Northern Ghana and are described in Section 6.0.

7.1 Description of Dams

The physical water characteristics of four dams near Tamale were studied: Ghanasco Dam, Gbrumani Dam, Kpanvo Dam, and Kunyevilla Dam (Figure 34).



(Map by J. VanCalcor, 2007)

Figure 34 Map of Tamale and locations of dugouts

Ghanasco Dam is located along the hospital road near Vittin Estates, Tamale. It is a larger dam that does not dry up. Many people frequent the dam ad come from numerous surrounding semi-urban communities to collect water directly from the muddy shores of the dam. It does not have a fence, reeds, or grasses around its periphery. This dugout was the site of the author's pilot horizontal roughing filter (HRF) study.

Figure 35 Ghanasco Dam, Tamale (site of pilot HRF)
Photo Credit: Susan Murcott

Gbrumani Dam is located in the Tolon District. The community received aid from Rotary International and the Carter Foundation to fence in the dugout and install hand pumps with gravel infiltration galleries at the mouth of the intakes. Two types of samples were taken from the Gbrumani Dam; one hand pump water sample taken after the water had gone through an infiltration gallery of sand and gravel and one directly from the dugout. At the time of the visit, the women and children collecting water were only using water from the hand pumps and did not collect water from the dam. The Gbrumani Dam also had tall grass around the periphery of the dam, a type of natural watershed protection that prevents particulate matter from entering the dugout in rainwater runoff.

Figure 36 Gbrumani Dam and hand pumps, Tolon District

Kpanvo Dam is the main source of water for Kpanvo, a community in southwestern Tamale that had recently received five treadle pumps from the Guinea Worm Eradication Campaign (GWEC) so that individuals would not wade into the dam to collect water. The treadle pump spouts were covered by Guinea worm cloth filters to ensure that any water collected was filtered through a cloth filter (Figure 38 and 5.3.1.1 Guinea Worm). Although after three days of use, two of the five treadle pumps were already in need of repair, the beneficiaries were using the remaining three pumps. All individuals also received free pipe filters from the GWEP while free biosand filters were disseminated by International Aid. Kpanvo was also a community where Pure Home Water had sold a limited number (7) of Kosim ceramic pot filters. Kpanvo Dam's surface area was smaller than Ghanasco Dam and its periphery was also denuded of reeds and grasses. We were informed that it would dry up with the next 1-2 months (March, April) at which point the community would need to purchase water.

Figure 37 Kpanvo Dam before (above) and with treadle pump (below)
Photo Credit: Kelly Doyle (left)
GPS: Lat. 09º21.725', Long. 000º49.191'

Kunyevilla Dam is located near Tamale has a large surface area, no periphery fence, and very little grass along its clay-packed periphery. It was drying up very quickly at the time of the visit on January 21, 2008. Women purchase water from Tamale once the dam is empty. Taysec Construction Company, an international construction company that builds roads in Ghana, enlarged the dam in April 1997. In 2002, the local NGO, Village Water, built a system to treat dugout water in a covered channel and store it in a cistern fitted with two rope and washer hand pumps. The dugout water flows through three 4-inch diameter pipes, a 28-meter long, concrete-lined channel partially filled with large gravel, a covered 16-meter long concrete channel filled with sand, and finally reaches the sunken cistern. (See Section 10.1 Kunyevilla Dam Channel for more information.) By January 21, the dugout was so low that water no longer filled the cistern. Many of the channel coverings had been removed. The channel held contaminated stagnant water and was in a state of disuse. At the time of the visit, beneficiaries were collecting water directly from the dam.

Figure 38 Kunyevilla Dam
GPS: Lat. 09º23.799’, Long. 000º53.242’

7.2 Physical Water Quality Results

The following results are the first step in trying to differentiate how land use practice and water resource management can impact the turbidity and general water quality of dugouts in Northern Region, Ghana.

7.2.1 Ghanasco Dam Turbidity Analysis

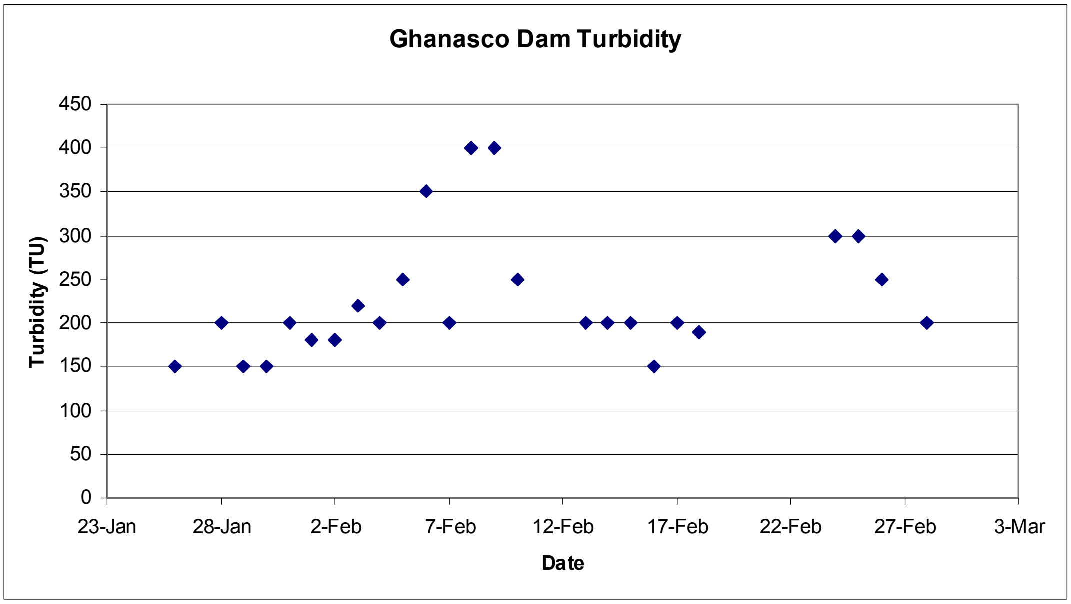


Figure 39 Ghanasco Dam turbidity during dry season, Tamale

Figure 39 presents an initial upward trend in turbidity values for Ghanasco Dam as the water is used and evaporates in the course of these 2 dry months of January and February[21]. The results follow this trend until about February 10th when the turbidity dropped about 270 NTU (200 TU) and stayed between approximately 270 NTU (200 TU) and 450 NTU (300 TU)[22].

7.2.2 Filtrability of Various Dams

According to the WHO DWQGs, turbidity can be a parameter used to evaluate types and levels of treatment (WHO, 2004). The relative particle size and distribution of water sample can be determined with a filterability test. Water samples with very low filterability could require a turbidity removal step such as RF prior to SSF.

Figure 40 compares the filterability of water samples from four dams and one of those dams' infiltration gallery and hand pump system. The dams were all in Northern Region Ghana but differed in turbidity (Table 12), the way the water was accessed and the way measures were taken to prevent livestock from entering and contaminating the water.

Table 12 Dam Turbidities when Sampled (January 2008)

Source:	Ghanasco Dam	Gbrumani Dam	Gbrumani Hand Pump	Kpanvo Dam	Kunyevilla Dam
Turbidity (NTU):	227	48	28	116	124

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[21] Some of the turbidity measurements for the Ghanasco dam are taken from Kikkawa (2008).

[22] Turbidity units (TU) were converted to nephelometric turbidity units (NTU) using a correlation found between TU and NTU data and presented in Appendix D: Relationship between Nephelometric Turbidity Units (NTU) and Turbidity Units (TU).

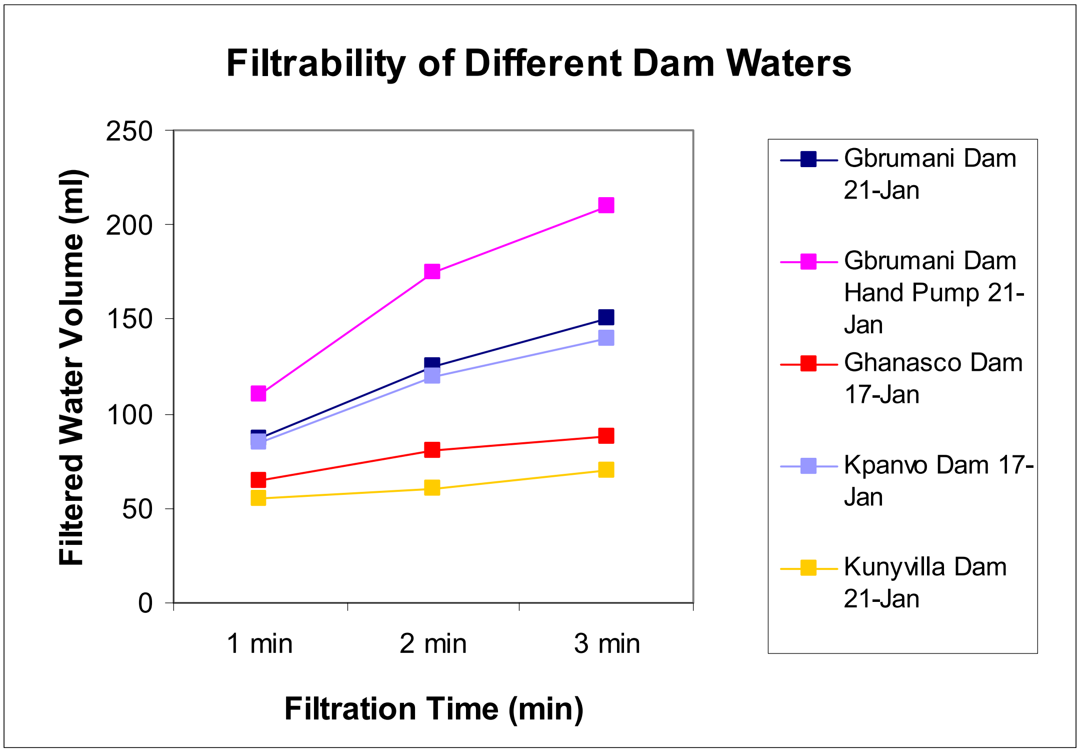

Figure 40 Comparing the filterability of different dam waters, Northern Ghana (January 2008)

The Gbrumani Dam hand pump sample had the fewest particles. Kpanvo Dam and Gbrumani Dam had about the same amount of particulate matter. Out of these four dams, the Kunyvilla Dam and Ghanasco Dam water samples had the greatest suspension of particulate matter.

Wegelin suggests in the *Surface Water Treatment Manual* that SSF is only appropriate when the influent filterability value is at least 200 ml in 3 minutes or higher and the effluent is at least 300 ml in 3 minutes. The dugout filtrabilities in Figure 40 show the raw dugout water from all three dams is not adequate for SSF. According to this guideline, all four dams require pretreatment prior to SSF. Although the dugout water could be directly filtered through SSF, the large amount of suspended particulate matter would cause the SSF to have short filter runs. Only the Gbrumani Dam hand pump water would be appropriate for SSF because 200 ml flows through the 1.5µm filter in 3 minutes. Therefore, some type of pretreatment of the raw dugout water is necessary if SSF is to be successfully implemented as a community-based intervention to improve drinking water quality in Northern Ghana.

7.2.3 Solids Settleability

This test was conducted twice; once with Ghanasco Dam water (January 17, 2008) and another time with Kpanvo Dam water (January 17, 2008). In both cases, less than 1 ml/liter settled after 24 hours. This suggests two possibilities; the dugout serves as a natural passive sedimentation tank removing many of the more massive, larger particles and/or particles in the dugout water are colloidal and remain suspended in the water.

Although higher temperatures will cause the water to be less viscous, the very small particle sizes prevent settling from significantly speeding up. Wegelin warns that raw water with an initial turbidity of 50-100 NTU or higher that only accumulates 1 ml/liter of settleable matter after 24 hours will most likely be difficult to treat by HRF because of the presence of small colloidal particles (Wegelin, 1996). In such cases, pilot plant tests, such as the one performed at Ghanasco Dam, are required to determine the appropriate pretreatment step.

7.2.4 Suspension Stability of Dam Water

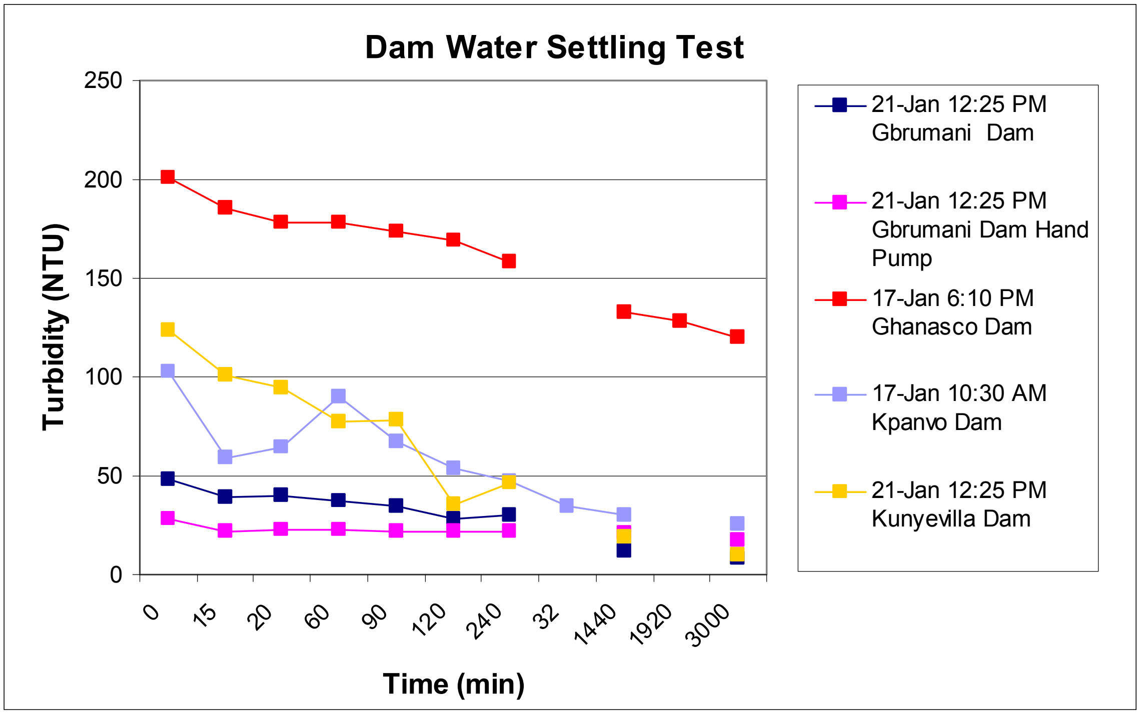

Figure 41 Suspension stability of dam water

All of the initial turbidities in Figure 41 decreased after settling for approximately two days. The Gbrumani Dam hand pump sample began with the lowest turbidity and experienced a slight reduction in turbidity in during the settling period as it reached 20 NTU. Gbrumani Dam, on the other hand, began at approximately twice the turbidity (50 NTU) and finished at about 10 NTU, a turbidity slightly lower than the Gbrumani Dam hand pump. Kpanvo Dam and Kunyevilla Dam initially start at about 100 NTU and 125 NTU respectively. Much of the particles responsible for their turbidities settled so that the final Kpanvo Dam and Kunyevilla Dam turbidities were about 30 NTU and 10 NTU respectively. Ghanasco Dam had the highest initial and final turbidity. Although half of its turbidity was removed through settling in two days, its final turbidity was high at about 125 NTU.

7.2.5 Sequential Filtration

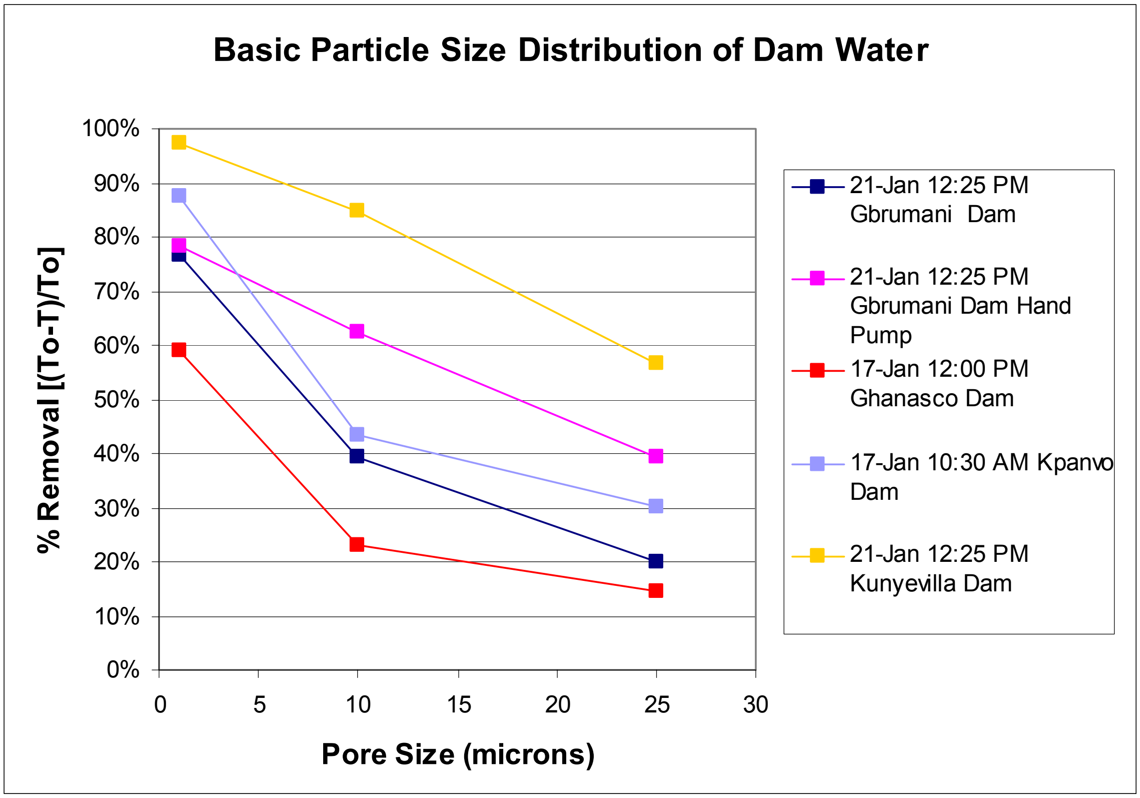

Figure 42 Results from sequential filtration of dam water

Figure 42 illustrates the percent turbidity removal from filtering water through 1µm, 8-12µm, and 20-30µm polycarbonate capillarpore membrane filters. Kunyevilla Dam's turbidity was barely reduced after filtering through the 1µm filter but experienced increasing turbidity removals as the filter pore size increased to 8-12µm and then 20-30µm. Similarly, the 1µm filter only removed about 10% of the Kpanvo Dam turbidity. The 8-12µm filter removed even more turbidity from Kpanvo Dam. The turbidities of the Gbrumani Dam and hand pump both were reduced by 20% after flowing through the 1µm filter. However, after the 1µm filter, the Gbrumani Dam and the Gbrumani Dam hand pump turbidities diverged. The Gbrumani Dam hand pump turbidity continued to be reduced by about 20% after each filter. The Gbrumani Dam experienced a 40% turbidity reduction after the 8-12µm filter and a 20% turbidity reduction after the final 20-30µm filter. Ghanasco Dam's turbidity was reduced by 40% after passing through the 1µm filter, another 40% after the 8-12µm filter, and less than 10% after the last 20-30µm filter.

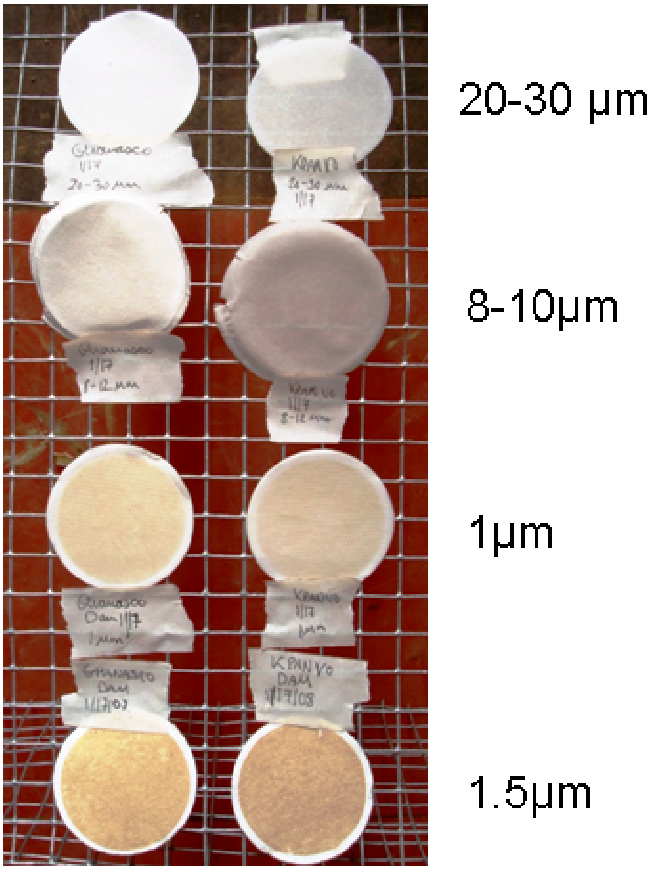

Figure 43 Filter papers from Ghanasco Dam (left) and Kpanvo Dam (right) filtrability tests (1-17-08)

Visual analysis of the filter papers in Figure 43 show that as the filter pore sizes decrease more colored, organic material is removed from the Ghanasco Dam and Kpanvo Dam water.

7.3 Analysis and Discussion of Physical Water Quality Results of Dams in Northern Ghana

Although these results make a contribution towards a better understanding of the physical water quality characteristics of dugouts, it must be understood that they do not account for temporal and seasonal variation. They represent the water's physical characteristics the day the water was sampled in January 2008.

7.3.1 Analysis of Ghanasco Dam Turbidity Results

As previously stated, the Ghanasco Dam turbidity values increased with time until about February 10 when the turbidity greatly decreased (Figure 39). This is very odd turbidity behavior for the dry season months because with dugout use, hot weather, and evaporation the remaining water should become dirtier and more turbid. Variation in the sampling technique, location, and/or the turbidity measurement could have caused this drop in turbidity. In addition, it is difficult to take accurate turbidity readings with the turbidity tube because measurements can vary person-to-person and with the light conditions.

7.3.2 Analysis of Dam Setting Tests

The results of suspension stability test in Figure 41 not only illustrate the differences in turbidities between the four dams and the Gbrumani Dam hand pump but also give an idea of the relative size of particles that contribute to that turbidity. The Gbrumani Dam hand pump sample has the lowest initial turbidity out of all of the results and notably begins at a lower initial turbidity than the Gbrumani Dam. After two days of settling, the Gbrumani Dam and Gbrumani Dam hand pump samples ended at turbidities of 10 NTU and 20 NTU respectively showing that smaller non-settleable particles contributed to the Gbrumani Dam hand pump turbidity.

Kpanvo Dam and Kunyevilla Dam have similar particle characterizations according to the settling results because the particles contributing to their turbidities settle out in the same way; both begin with a turbidity close to 100 NTU and 125 NTU respectively. However a smaller part of the Kpanvo Dam turbidity is removed by settling than Kunyevilla Dam turbidity. This suggests that Kunyevilla Dam has slightly larger particles than Kpanvo Dam. A much greater portion of the turbidity from Kpanvo Dam and Kunyevilla Dam are able to settle out in comparison with Ghanasco Dam whose turbidity begins the highest (200 NTU) and is able to settle out to less than half of the turbidity to end at 125 NTU. If the settling rate is used as a measure of relative particle size, Kunyevilla Dam has the largest particle sizes and Ghanasco Dam the smallest.

7.3.3 Analysis of Dam Filtrability

The more turbid the water, the more likely the suspended particulate matter will clog the filter reducing the volume of effluent water measured at 1, 2, and 3 minutes. With this in mind, the data in Figure 40 can be divided into three sections; the Gbrumani Dam hand pump sample, Kpanvo Dam and Gbrumani Dam, and finally Kunyevilla Dam and Ghanasco Dam. Because the Gbrumani Dam hand pumps sample had the most water filter through, it has the fewest particles greater than 1.5µm in size. Kpanvo Dam and Gbrumani Dam follow a similar trend and have an intermediate amount of particles. From the previous section, 7.3.2 Analysis of Dam Setting Tests, the results suggested that Ghanasco Dam's high turbidity is characterized by a large amount of colloidal particles while larger, more settleable particles characterize Kunyevilla Dam's high turbidity. Kunyevilla Dam and Ghanasco Dam behave similarly with respect to their filtrability. However, the filtrability results suggest the main cause of Kunyevilla Dam's low filtrability is larger particles while Ghanasco Dam's low filtrability is caused by a large concentration of colloidal particles.

7.3.4 Analysis of Dam Sequential Filtration

A smaller percent removal with a specific filter size indicates a greater number and/or mass of particles smaller than the pore size flowed through the filter. The converse is also true; a larger percent removal for a certain filter size implies that there are more particles contributing to the turbidity that are larger than the filter size. The percent turbidity removals do not add up to 100 percent removal because some of the particle sizes lay above and below the tested ranges.

Ghanasco Dam had the largest turbidity removal percent using the 1µm filter because, as seen in the previous two analysis sections, its water is characterized by small colloidal particles less than 1µm in size. The Ghanasco Dam sample experiences another 40% reduction in turbidity due to particles that are between 1.5µm and 10µm in size. Therefore, approximately 80% of Ghanasco Dam's turbidity is influenced by colloidal and supracolloidal particles less than 10µm in size.

The sequential filtrability results from Kunyevilla Dam contrast with Ghanasco Dam's because more turbidity is removed with the 20-30µm than the smaller filter papers. This reinforces the results from the settling and fitrability tests; that Kunyevilla Dam contains larger particle sizes.

Again, Kpanvo Dam and Gbrumani Dam's turbidity values behave similarly with the largest percentage (approximately 40%) of turbidity removed in the 1.5-10µm range and approximately 20% removed below 1.5µm and between 10-25µm. Therefore, Kpanvo Dam and Gbrumani Dam have mainly medium-sized supracolloidal particles ranging from 1.5-10µm in size.

The Gbrumani Dam hand pump sample results behaved as expected. These results suggest that the Gbrumani Dam hand pump has equal proportions of particles in the less than 1.5µm, between 1.5µm and 10µm, between 10µm and 25µm, and greater than 25µm. Because the very little turbidity settled out previously, it was expected that the Gbrumani Dam hand pump samples would a particle size distribution of mostly colloidal and supracolloidal particles similar to Ghanasco Dam or Gbrumani Dam.

7.4 Microbial Water Quality of Ghanasco Dam and Kpanvo Dam

Membrane filtration tests on raw water from Ghanasco Dam and Kpanvo Dam showed that both dugouts had very high levels of microbial contamination that greatly exceed the WHO's drinking water guideline of 0 *E.coli* CFU/100 mL of drinking water (WHO, 2004).

Table 13 Microbial Contamination in Ghanasco Dam and Kpanvo Dam (January-February 2008)

Source	**Average *E.coli* CFU/100 mL**	**Average Total Coliform CFU/100 mL**	**Average Tubidity (NTU)**
Ghanasco Dam	8,375	8,400	350
Kpanvo Dam	271,750	323,000	116

7.5 Soil Arsenic and Lead Results from Ghanasco Dam

Table 14 shows that one soil sample from the periphery of Ghanasco Dam had low levels of arsenic and lead.

Table 14 Arsenic and Lead Levels in Ghanasco Dam Surface Soil Sample (January 2008)

	Arsenic (ppm)	**Lead (ppm)**
Ghanasco Dam clay surface soil	5.8	21.0

8.0 Pilot Horizontal Roughing Filtration System at Ghanasco Dam, Tamale

8.1 Description of Ghanasco Dam Field Site

Ghanasco Dam, a large semi-urban dugout located to the northeast of Tamale, near Vittin Estates, was chosen as the horizontal roughing filter (HRF) pilot test site (Figure 45) (see Section 7.2 Physical Water Quality Results). Two important factors were considered when choosing the location of the pilot system. Firstly, the dam needed to have highly turbid water between 200 NTU and 500 NTU during the test. Ghanasco Dam's average turbidity during the test was 277 TU (approximately 270 NTU[23]). Secondly, the dugout's proximity to the Peace Corps Tamale Sub Office (TSO) and to the Tamale market were important for purchasing and transporting materials during construction, taking water samples back to the TSO (where the laboratory was located), and monitoring the system.

Figure 44 Ghanasco Dam, Tamale, Northern Region Ghana

(Map by J. VanCalcor, 2007)

Figure 45 Location of Ghanasco Dam, Tamale, Northern Region Ghana

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[23] TU is converted to NTU using the TU-NTU correlation found in Appendix D: Relationship between Nephelometric Turbidity Units (NTU) and Turbidity Units (TU).

This pilot study lasted 52 days from January 13 until February 28, 2008[24]. The ideal months to run the pilot test would have been during the highest raw water turbidity in the rainy season, however, due to schedule constraints, this was not possible. Cost also limited the duration of the pilot test. The major costs of the project were the construction materials for the pilot test setup and paying day and night guards to keep watch over the system to insure there was no vandalism or theft.

8.2 HRF Pilot Design

Figure 46 Ghanasco Dam HRF pilot system (January-February 2008)

The pilot system design was made from low-cost, locally available materials to determine if HRF could reduce the turbidity of highly turbid dugout water. Pilot systems described by Wegelin in Section 11.2 of the *Surface Water Treatment by Roughing Filter* included both a RF and SSF because the turbidity removal efficiency of the RF was based on the headloss development in SSF. The pilot HRF at Ghanasco Dam only included a RF. Therefore, instead of determining whether RF are appropriate for the specific raw water characteristics based on headloss in the SSF, the focus was on the RF's ability to reduce the raw water turbidity to below 50 NTU, a level where SSF can operate.

In the physical water quality tests described in Section 7.0, it was found that samples tested from raw dugout water in particularly from Ghanasco Dam contained many colloidal particles. These colloidal particles could be problematic and impede RF removal of turbidity if they are too small and do not settle fast enough to reach and stick to the RF media's biofilm. Therefore, a pilot HRF was constructed to test the applicability of basic HRF design parameters[25] to surface water quality conditions in Northern Ghana (Table 8). The second purpose of testing the HRF's turbidity removal efficiency was to investigate a design concept; to build a HRF in a concrete-lined channel and transport the raw water through the HRF by gravitational flow, eliminating the need for mechanical pumping (Figure 47). At the end of the channel, the water passes through a SFF, and then moves to a partially underground cistern. Not only would this simplify the system by reducing the cost of pumping but it would also limit the amount of mechanical parts that could break and need to be repaired and would facilitate ease of access for cleaning.

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[24] The recommended time for RF pilot studies are 180 days (Wegelin, 1996).

[25] These design parameters are detailed in Table 15.

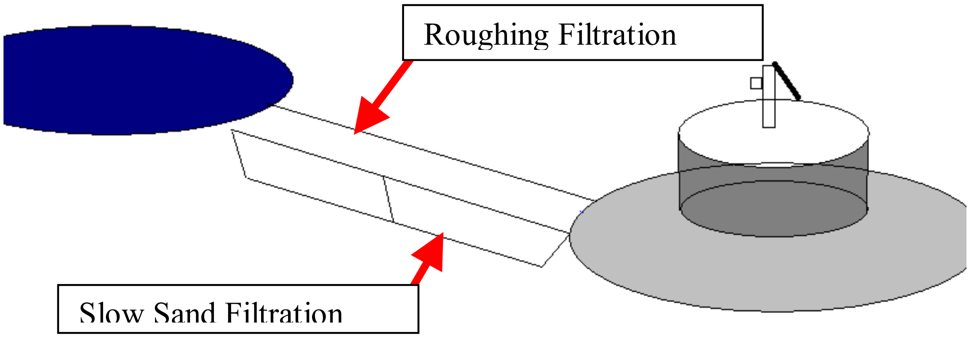

Figure 47 Multistage HRF-SSF canal from dugout with sunken cistern and hand pump

8.3 Construction of Pilot HRF

The construction of the HRF was completed with locally available PVC pipe and two 700L polytanks (Figure 45, Figure 48, Figure 49 and Figure 55). The polytanks were elevated 54cm off the ground and sat on a base of concrete cinderblocks and mud bricks. The 4" PVC pipe was laid on the more-or-less level ground. The end of the 7 meter 4" PVC pipe was capped with a 90 degree elbow and angled upward so that the bottom lip of the effluent would be above the top of the tube, maintaining the tubes full of water at all times (Figure 28 and Figure 50). Table 15 shows the different filter lengths and the range of media sizes for each HRF section.

Table 15 Ghanasco Dam Pilot HRF Design Dimensions

Filter Section	Filter Length (m)	Media Size (dg_x) (mm)
First	3.5	12 – 18
Second	2.5	8 – 12
Third	1	4 – 8

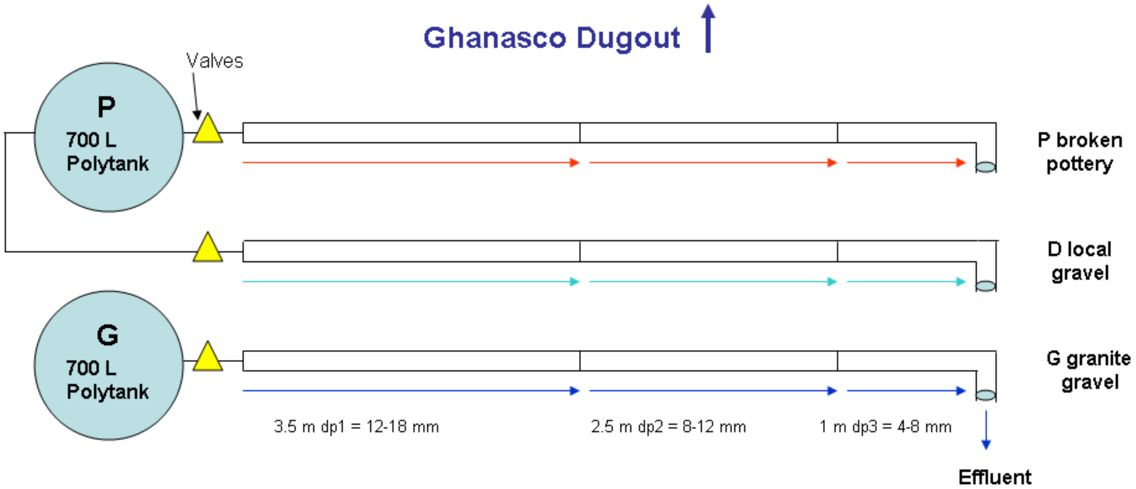

Figure 48 Ghanasco Dam pilot HRF design from above

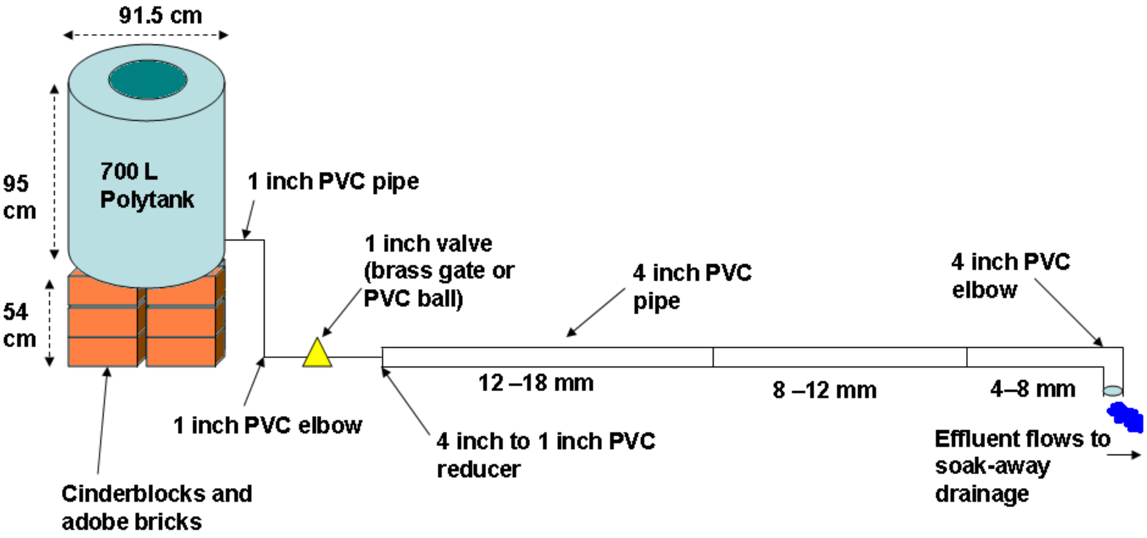

Figure 49 Detailed design of the Ghanasco Dam pilot HRF

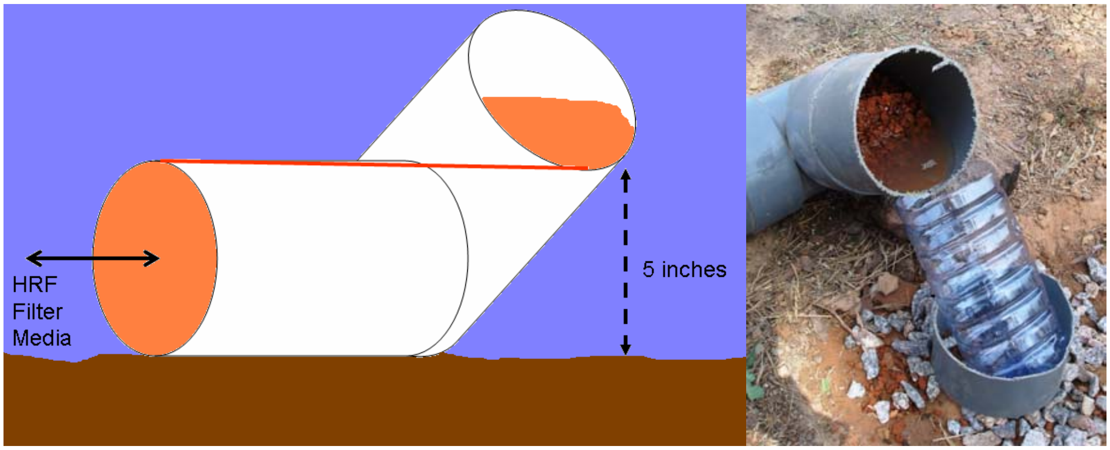

Figure 50 Design of end of pilot HRF PVC pipe

It took more than one week to transport clean gravel and other materials to Ghanasco Dam, purchase PVC piping, break pottery pieces to designated sizes (Figure 51), sieve and sort the media by size, and assemble the system.

Table 16 Cost Comparison of Roughing Media (January 2008)

Media	**Price per m^3 (GHC)***	**Price per m^3 (US$)**
Granite gravel (G)	81.77 GHC	$79.67
Local gravel (D)	8.13 GHC	$8.16
Broken ceramic filters (P)	free from Pure Home Water	free from Pure Home Water

*1.025 GHC was equivalent to approximately US$ 1.00 according to the exchange rate on January 2008 from http://www.oanda.com/convert/fxhistory.

Figure 51 Carl Allen (Peace Corps) and the author breaking ceramic pottery pieces for the pilot HRF

Figure 52 Pilot HRF media: granite gravel (G) left, local gravel (D) center, broken pottery (P) right

The media was cleaned before being sorted by size. To clean the media, a small amount was placed in a plastic sieve and plunged in clean water three times. The sieve basket was then passed to the next water bucket and plunged into the water three times. Finally, this was repeated a third time or until further plunging did not dirty the water (Figure 53). Mesh screens with 5 mm openings were used to separate the 4-8 mm pieces. Screen sieves with 13 mm openings were used to with separate the medium-size 8-12 mm media. The largest media were taken from what remained on the 13 mm screens by inspection.

Figure 53 Breaking and sieving pottery (left), Baba cleaning pottery with sieves (center-left), Kim Weaver (Peace Corps) cleaning pottery (center-right), Carl Allen (Peace Corps) pre-filtering dugout water with bed sheet to remove copepods before using the water to clean local gravel (right)

To try to pack the media well, minimize areas left without media, and, thus, prevent side-walling of flow along the tube walls, the tubes were filled at an angle by starting from one end and allowing the media to slide down (Figure 54). The image of the packed local gravel (D) in Figure 54 suggests that the tube was fairly well packed although some settling of the media could have left gaps along the top the tube. At first just two tubes where set up; granite gravel (G) imported from Burkina Faso but purchased locally in Tamale and unglazed pottery pieces (P) from *Kosim* ceramic filters that had broken and been donated by the NGO Pure Home Water. Later, another tube of gravel was added and in it softer, local gravel (D) that had a dirty clay color was used (Figure 52).

Figure 54 Filling pilot HRF tube with media (left), fully packed D tube with media (right)

Table 17 Ghanasco Dam Pilot HRF Media Porosity

Media	**Media Size (mm)**	**Porosity[26]**
Granite gravel	4-8	0.51
	8-12	0.49
	12-18	0.45
Local gravel	4-8	---
	8-12	---
	12-18	---
Broken pottery pieces	4-8	0.72
	8-12	0.65
	12-18	0.70

Although granite gravel (G) and broken pottery pieces (P) were similarly sorted, their respective average porosities are approximately 0.50 and 0.70. Part of this 20% difference in porosities was the extra water absorbed by the pottery pieces in their

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[26] The porosity of HRF tubes packed with media was determined in the MIT laboratory by weighing a beaker filled with dry media, a beaker filled with water and media, and taking the difference between the to masses. Using the density of water (1000g/L), this difference was converted to the water volume that occupied the porous spaces. Porosity was found by taking the ratio of the water volume or the porous spaces to the total volume.

saturated condition. Ceramics hold more water than gravel when the medium is saturated with water but the surface is dry in their surface-dry condition.

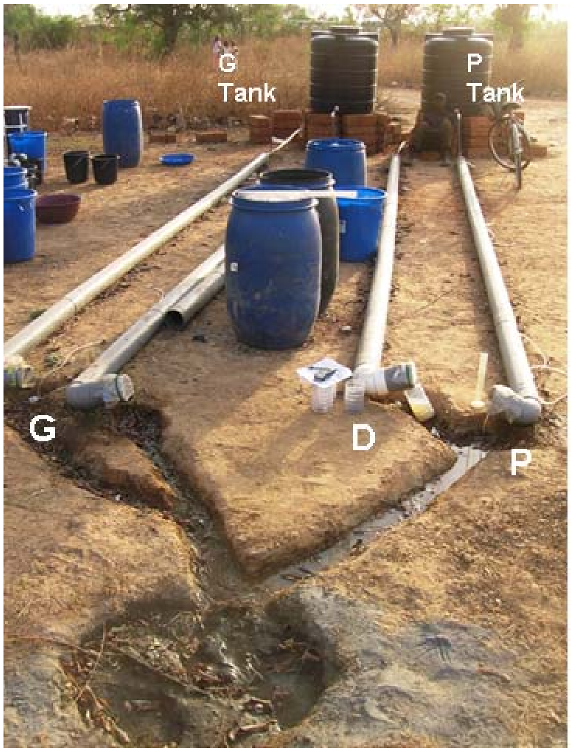

Figure 55 Pilot HRF Ghanasco Dam, Tamale, Ghana
Photo Credit: Carl Allen

8.4 Methods for Operating and Monitoring the HRF System

The author, Tamar Losleben, operated and monitored the pilot HRF system from January 18 to January 24, 2008. Carl Allen, Ghana Peace Corps Volunteer Leader, (PCVL) was instrumental in filling the tanks, adjusting the flow rates, and measuring the flow rates and turbidities of the pilot system after the MIT team's departure from January 26, 2008 until February 28, 2008.

8.4.1 Pilot HRF Flow Rate Measurement

Monitoring the HRF system included daily measuring of the flow rate before samples were taken from the HRF effluent. To measure the flow rate, a one liter beaker was placed at the lip of the HRF tube and allowed to collect the effluent for one minute. At the end of one minute, the volume of water collected was measured.

8.4.2 Tank Level

From January 13 to January 18, the tanks were filled to different levels with buckets of water from the dugout. It was important to establish a regimen for filling and mixing the tanks in order to guarantee consistency in these measurements. The fill level and time when they were filled was also recorded. Starting January 18 until January 24, 2008, the P and G tanks were filled to 35 cm depth at the same time the system was monitored. This time was noted. From January 25 to February 28, 2008, the night guard filled both tanks to 35 cm and usually did so at 6 am. There could have been some irregularity in their schedule, so it should not be assumed that they followed this scheduled strictly.

Figure 56 G and D tanks from left to right
Photo Credit: Carl Allen

8.4.3 Mixing

For the first two days, January 13 and 14, neither tank was stirred. Starting January 15, the tanks were mixed three times a day at 6 am, 12 pm, and 6 pm. After January 19, when the mixing became the day and night guards' duty, the mixing was increased to four times a day by also mixing both tanks at midnight. Mixing the tanks helped re-suspend the particulate matter that had settled and accumulated in the tank however the intensity of mixing was variable.

For the best performance, the HRF requires that there be continuous flow of raw water through the roughing media (Wegelin, 1996) (Gerardo, 2006). The HRF tube effluent was collected in small channels into a 1 meter deep soak-away, a dug hole filled with gravel. Flow from the polytanks was regulated by 1" valves between the tank and 4" tube (Figure 57). Unfortunately, the low flow rates required of a HRF were difficult to regulate with the sticky valves. Between visits to the system, the small openings of the valves quickly became clogged and stopped the flow through PVC tubes. Initially PVC ball valves from the United States were installed in the G and P tubes. When the D tube was added, all of valves were changed to locally purchased 1" gate valves (Figure 57). These were easier to regulate but still clogged. For these reasons and the constantly changing head, it was difficult to maintain constant flow conditions. Interestingly, Wegelin (1996) warns that valves are not recommended because they clog easily especially with flow rates lower than 0.5 L/min. With the target flow rates ranging from 135 ml/min to 270 ml/min, all values were below the limit. Unfortunately, the local gravel tube's valve broke on February 13, 2008 after about five weeks of operation (36 days) and was not repaired to enable completion of that tube's pilot treatment. The G and P tubes ran for a total of 52 days.

Figure 57 Pilot HRF valves: 1” PVC ball valve (left) and brass gate valve (center and right)

The tank levels, tank settled and mixed turbidities, and G, D, and P turbidities and flow rates were monitored daily.

8.5 Pilot HRF Test Results

Figure 58 The author testing water samples in lab at the Peace Corps Tamale Sub Office, Ghana

8.5.1 Turbidity Removal

The HRF’s turbidity removal efficiency depends not only on the flow rate, ripening of the filter, and temperature, but also on the physical characteristics of the influent; its filterability, settleable solids, suspension stability, and sequential filtration results. Over time, the tank turbidity increased as particulate matter settled and accumulated in the tanks.

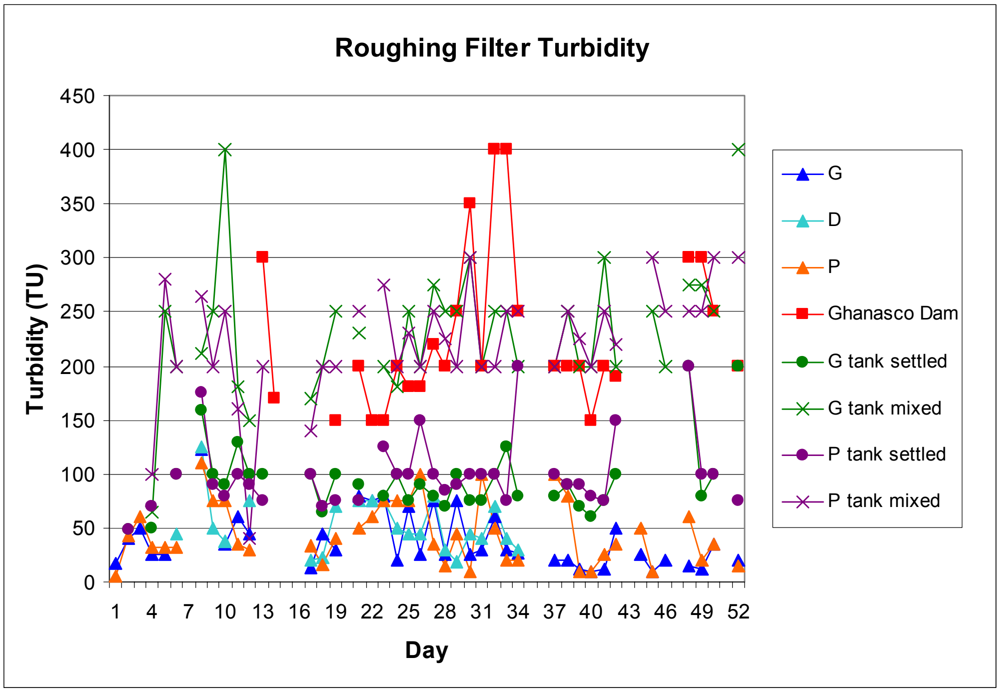

Figure 59 Ghanasco Dam pilot HRF turbidity

Table 18 Mean Turbidity Values for the Pilot HRF System at Ghanasco Dam

Tube	**G, Granite Gravel**		**D, Local Gravel**		**P, Broken Pottery**	
Source	G tank		P tank		P tank	
Average filtration rates when sampling (ml/min; m/hr)	220 ml/min 1.6 m/hr		170 ml/min 1.3 m/hr		200 ml/min 1.5 m/hr	
	TU	NTU	TU	NTU	TU	NTU
Average mixed tank turbidity*	232	313	223	301	223	301
Average settled tank turbidity*	95	128	101	136	101	136
Average % turbidity removal by tank settling	59%		55%		55%	
	TU	NTU	TU	NTU	TU	NTU
Average HRF effluent turbidity*	38	51	53	72	45	61
Average % additional turbidity removal by HRF after tank settling	61%		47%		55%	
Average total % turbidity removal in tanks and HRF	84%		76%		80%	

*This turbidity data was initial measured in TU with a turbidity tube and was converted to NTU using the correlation found in Appendix D.

Figure 59 presents turbidity data from the G tank and P tank and the G, D, and P tubes over the duration of the pilot test. In general, the Ghanasco Dam turbidity values coincide with the G tank and P tank mixed values (average values of 313 and 301 NTU respectively). This is expected and desired because the tanks were filled with dugout water and should have turbidity levels representative of the Ghanasco Dam (176 to 540 NTU). With turbidity removal as the main indicator of HRF efficacy, Table 18 shows that just through gravity sedimentation in the tank, the average turbidity percent removal was 59% in the G tank and 55% in the P tank. The HRF removed at least another 61%, 47%, and 55% of the turbidity in the G, D, and P tubes respectfully (Table 18). The average effluent turbidity[27] from all of the tubes was between 51 NTU and 72 NTU. This range of average effluent turbidities from the HRF tubes nearly satisfies the 20-50 NTU requirement for water being treated by SSF.

It is possible that the overall system was actually more effective at removing turbidity than presented here because the surface-value of the settled tank turbidity was used to calculate the average percent turbidity removal when in fact the turbidity was probably greater near the bottom of the tank where the outlet was located.

8.5.1.1 Comparison of Turbidity Removal at Different Flow Rates

The pilot HRF's flow rates strongly affected the resultant effluent turbidity values because the main mechanism for removing turbidity is settling. Not only was it difficult to set the different valves at the same flow rate setting but, as the level in the tanks decreased, the head loss for each system changed at different rates. The faster the flow rate, the less time the particle has to travel the settling distance and stick onto the media's biofilm layer. At the same time, higher flow rates were desirable because they produced greater quantities of water. Clearly, the HRF must also satisfy the water demand in addition to removing turbidity.

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[27] This turbidity data was initially measured in TU with a turbidity tube and was converted to NTU according to the correlation found between TU and NTU (Appendix D).

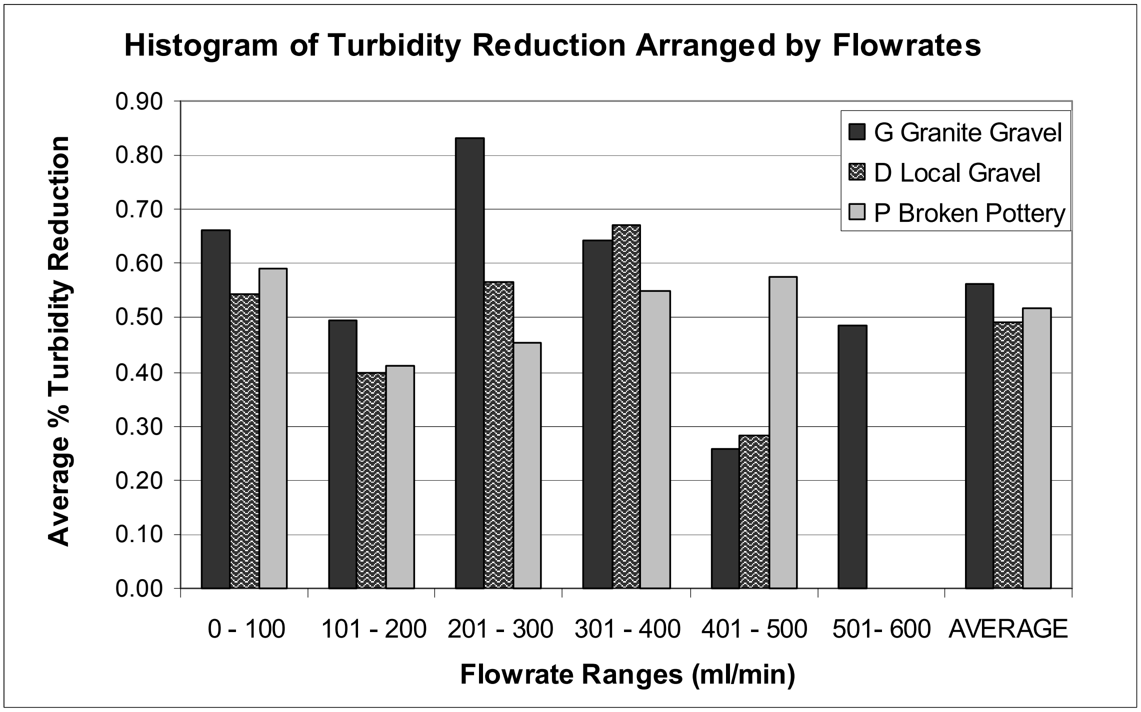

Figure 60 Comparing flow rate and turbidity removal in the pilot HRF

Figure 60 presents a histogram of the range of flow rates that were most effective at removing suspended particulate matter. It shows that the HRF flow rates were highly variable. Even within Wegelin's recommended range filtration rates, 0.3-2 m/hr (54-270 ml/min), none of the flow rate ranges had a clear advantage. Similar average turbidity percent removals for G, D, and P for the different flow rate ranges indicate that there is no clear preferable flow rate.

8.5.1.2 Improvement of Pilot HRF Turbidity Reduction with Runtime

Filter ripening as biofilm layers develop around the coarse media is an important process that is expected to improve the HRF's ability to remove turbidity. Ripening can occur in as few as 3 to 4 weeks, but can also take longer depending on the raw water quality and temperature. Although the data is fairly scattered, Figure 61 shows that as the runtime increases, the pilot HRF's turbidity removal efficiency improves slowly but steadily. This illustrates the ripening effect of the pilot HRF filter.

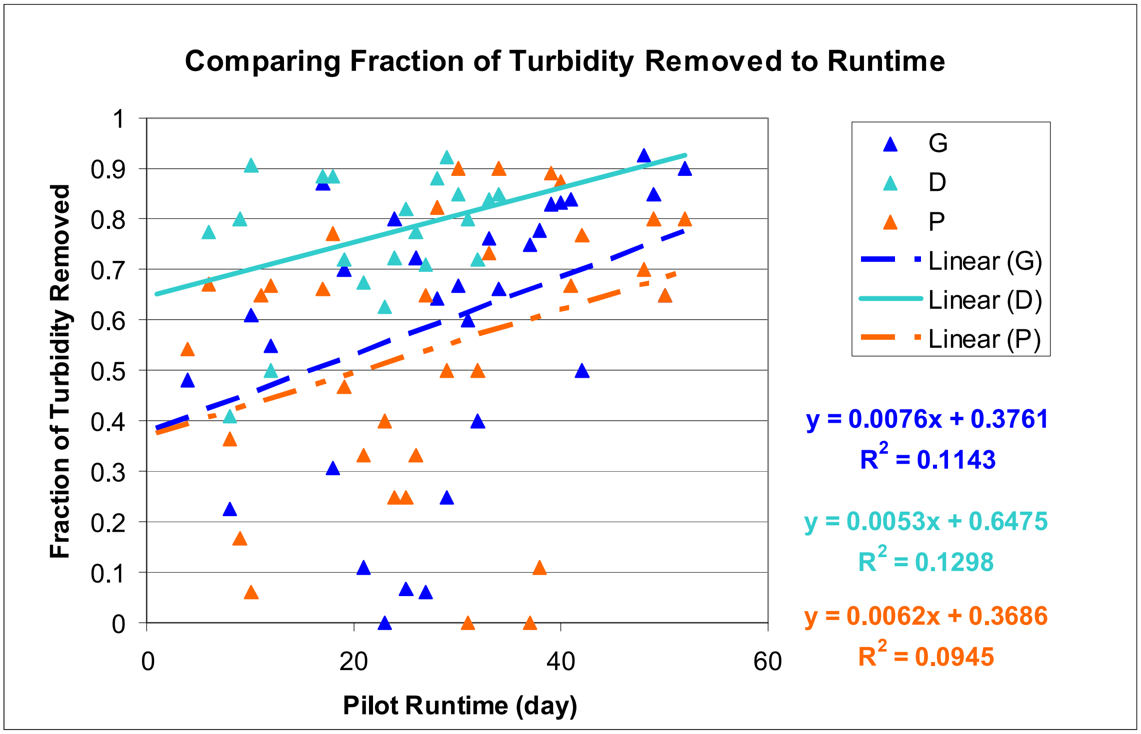

Figure 61 Improvement of pilot HRF turbidity reduction with runtime

8.5.4 Filtrability of HRF Influent and Effluent

Filtrability test results show the relative particle size distribution and are helpful in determining how well a filter is removing suspended matter. The greater the volume of water able to filter through the 1.5µm polycarbonate filter after 1, 2, and 3 minutes, the fewer particulate matter in the water. As seen in Table 19 and Figure 62, the average G and D effluents have much less suspended particulate than the mixed tanks and therefore faster filtered water volumes. Comparison between the settled tank and mixed G tank values (Figure 62) show that about half of the particulate matter is able to settle out in the tanks. Because of the difficulty of adjusting the valves, the G, D, and P tubes were usually set at different flow rates. Nonetheless, these results show that the G and D media removed substantial particulate matter by showing the faster flow times for those results.

Table 19 Average Filterability Values for Ghanasco Dam Pilot HRF (January 2008)

	1 minute	**2 minutes**	**3 minutes**
G tank	58	67	74
G effluent	76	106	123
P tank	63	76	84
D effluent	83	103	118
P effluent	59	75	84

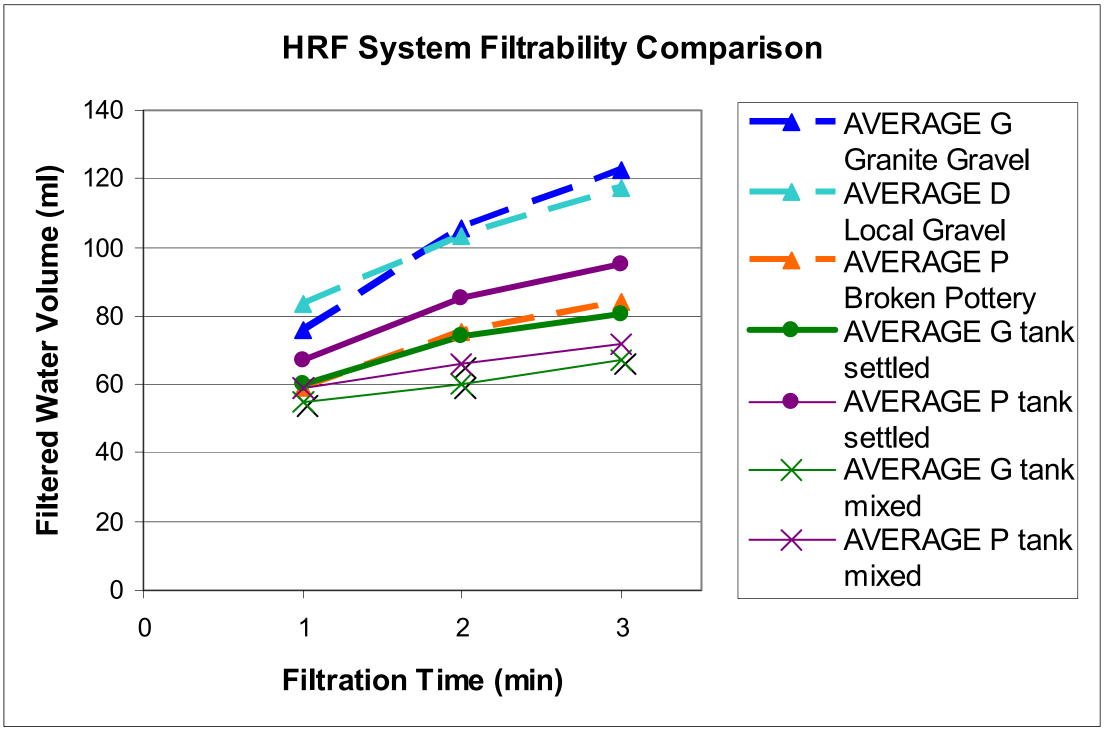

Figure 62 Pilot HRF system filtrability comparison

8.5.5 Settleable Solids in HRF Influent and Effluent

Similar to the previous settleable solids results in on dam water samples from the pilot HRF system all had less than 1 ml of settleable solids per liter of water. This suggests that the suspended particles are not very massive and/or that they are too small and light to settle out. Clay soils in Northern Ghana are a potential source of such colloidal particles because clay particles are less than about 1μm in size and are carried by runoff or deposited by the wind into the dugout.

8.5.6 Suspension Stability of HRF Influent and Effluent

Settling tests were conducted for water samples from the HRF tanks and HRF effluents.

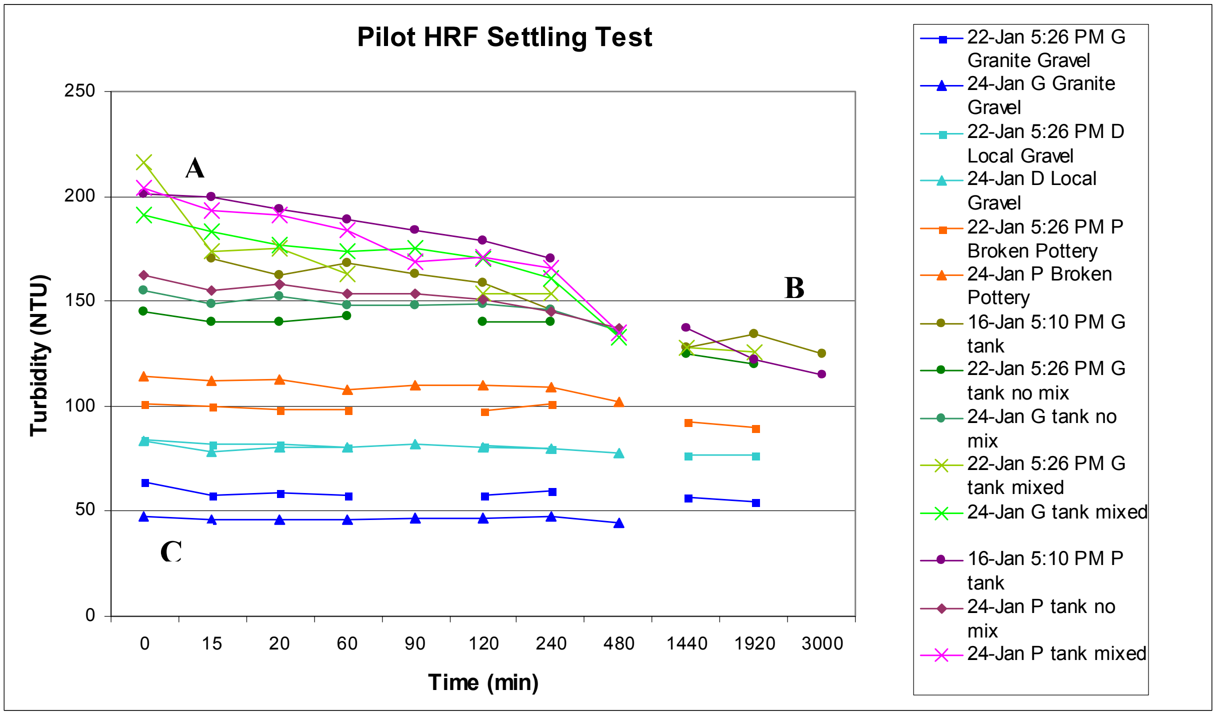

Figure 63 Settling tests for HRF tanks and effluents (G, D, and P)

Table 20 Comparing HRF Media Average Turbidity Removal Effectiveness with Settling Test Data

	G, Granite Gravel		**D, Local Gravel**		**P, Broken Pottery**	
Average flow rates (ml/min; m/hr)	218 ml/min		167 ml/min		194 ml/min	
	TU	NTU	TU	NTU	TU	NTU
Average influent turbidities* (A)	162	219	143	193	143	193
Average final settled HRF effluent turbidity* (C)	37	52	57	77	71	96
Turbidity removal by HRF** (B-C)	58	78	40	54	26	35
Average % turbidity removal by HRF [(B-C)/B]	46%		30%		19%	
Average % total turbidity removal by settling and HRF [(A-C)/A]	71%		58%		47%	
Average % turbidity removal by settling	25%		28%		28%	

*The average of the settled and mixed tank turbidities is used as the influent turbidity.

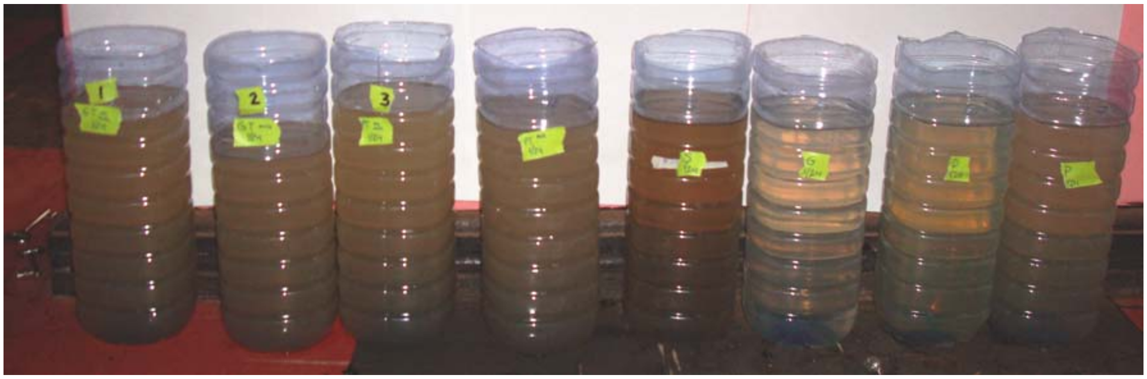

Figure 64 Pilot HRF suspension stability test (1-24-08)

Figure 63 illustrates the turbidity settling trends of two parts of the pilot HRF: the upper portion of the figure shows the settling behavior of tank water and lower portion shows the settling behavior of the HRF effluents. The settling tests showed that about 30% of the turbidity settled out of mixed tanks in 24 hours. After two days, the mixed tanks' turbidity leveled out at the settled tanks' turbidity values (Figure 63). Allowing the settled tank samples to settle further showed very little reduction in turbidity. Similarly, allowing the G, D, and P effluents to settle longer barely improved their turbidity. The amount of unsettleable particles represents the turbidity introduced by very small, colloidal particles such as clay.

The pilot HRF's efficacy at removing turbidity can be seen by comparing the HRF effluent turbidity values (G, D, and P) to the settled tank turbidity values in Table 20. The pilot HRF removed 46%, 30%, and 19% of turbidities in the G, D, and P tubes respectively. Including the effects of settling and the pilot HRF led to 71%, 58%, and 47% average total turbidity removals respectively for the three tubes. Subtracting the HRF percent turbidity removal from the total percent turbidity removals yields the percent turbidity removals from plain settling.

8.5.7 Sequential Filtration Tests of HRF Influent and Effluent

Sequential filtration utilizes the relative difference in turbidity between filtrates from different size filter papers to determine the proportion of suspended particles within that size range. An idea of the distribution of particle sizes can be gathered from Figure 65 by looking at the slope of the percent removal between pore sizes. The greater the difference between the percent removals between filter pore sizes, the steeper the slope, the more that range of particle sizes contributed to the sample's turbidity. For example, between 1µm and 10µm, which is the low-end of the supracolloidal size particle range, within which clay particles fall (1-5µm depending on the definition), average P and Ghanasco Dam have steeper slopes than D and the P tank. Therefore, particles between 1µm and 10µm contributed more to the turbidity in P and Ghanasco Dam than in average D and P tank.

In general, Figure 66 shows more turbidity was removed between the 1µm and 10µm sizes than between 10µm and 20µm pore size. This reaffirms that most of the particulate matter suspended in the dugout water, tanks, and HRF effluents (G, D, and P) are small colloidal and supracolloidal particles, less than 10µm in size. The average turbidity removal between the 1µm and 10µm microns pore sizes is 31% and for between 10µm and 20µm is 6%.

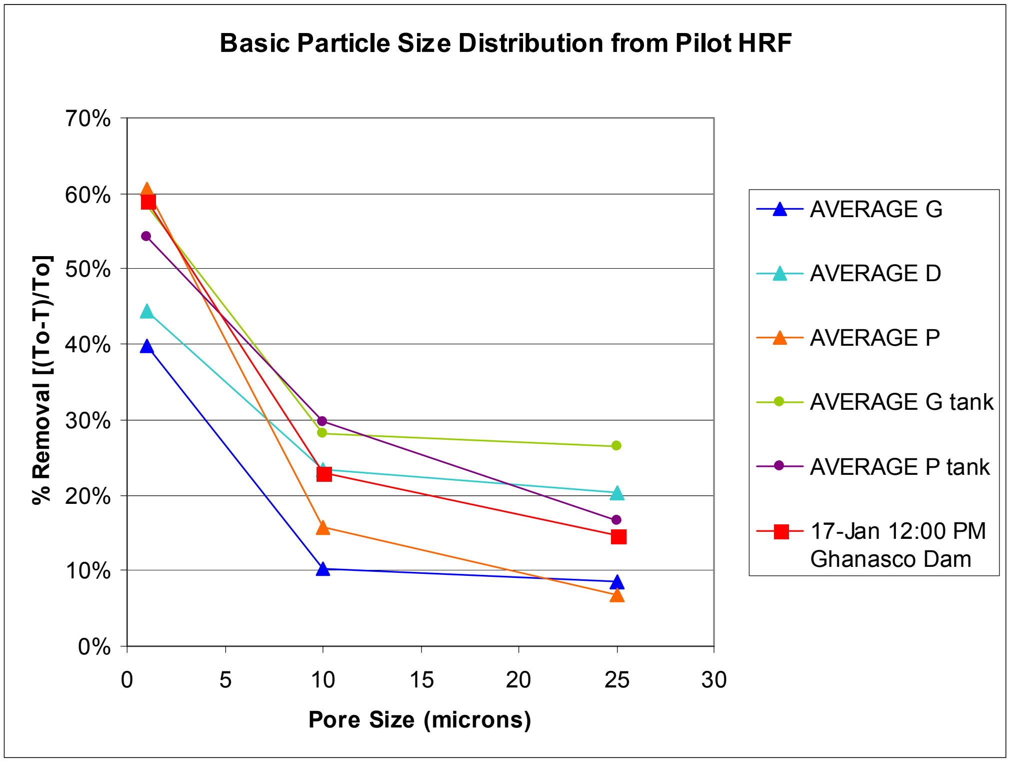

Figure 65 Pilot HRF basic particle size distribution from sequential filtration

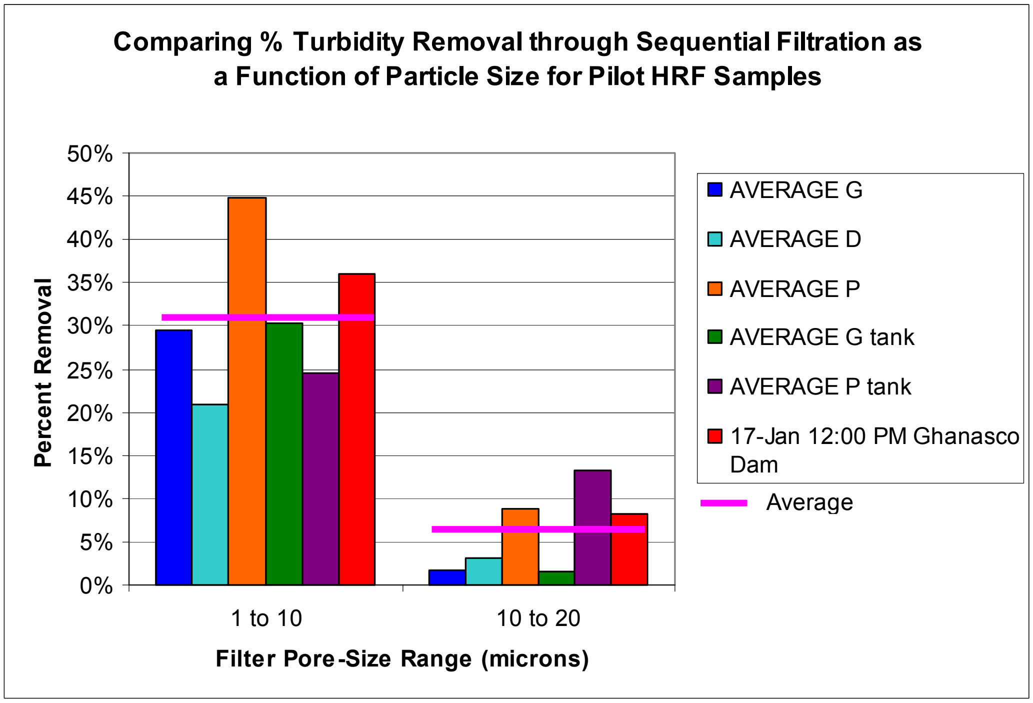

Figure 66 Decreases in percent turbidity removal through sequential filtration

It should be noted that the percent of turbidity removal does not equal 100 because there are particle sizes that are outside the 1 – 25μm range. Because the test was only completed once, a conclusive comparison between the HRF effluents and tanks' range of suspended particles sizes is not possible in Figure 65. However, general trends are still apparent in Figure 66.

This test assumes that particles mass is directly related to turbidity however the mass of particles is not exactly turbidity. One limitation of this test is that turbidity values for the HRF effluents are directly dependent on the variable flow rate while the tank turbidities depend greatly on how much the water has been mixed.

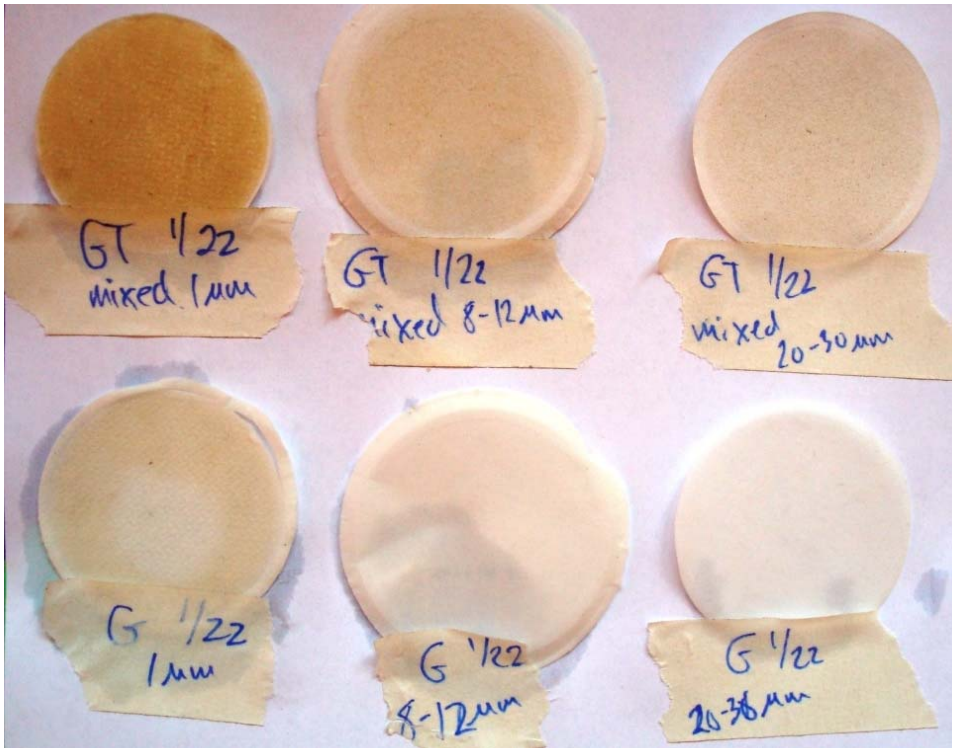

Figure 67 Filter papers from pilot HRF sequential filtration 1μm, 8-12μm, and 20-30μm across: G tank (top row) and G, granite gravel (bottom row) (1-22-08)

Visual analysis of the filter papers shows another interesting result when comparing the tank filter papers to the HRF effluent filter papers; there is color change between the influent and effluent of the HRF (Figure 67). While the former is brown probably due to organics it contains, the water exits the HRF filters with a chalky, white color.

8.5.8 Ghanasco Dam and Kpanvo Dam Microbial Contamination

As presented in Table 13 of Section 7.4, when tested in the dry season (January 2008), Ghanasco Dam's levels of *E.coli* (8375 CFU/100 mL) and total coliform (8400 CFU/100 mL) exceeded the WHO DWQG (2004) for 0 *E.coli* CFU/100 mL. In comparison with Johnson (2007) who found an average 779 *E.coli* CFU/100 mL for dams around Tamale for the dry season, the level of *E.coli* in Ghanasco Dam is especially high.

8.5.9 Arsenic and Lead in Ghanasco Dam Surface Soil

The surface soil sample from Ghanasco Dam had 5.8 ppm arsenic and 21 ppm lead. Acceptable levels of arsenic and lead in particles that could enter the dugout depend on the water's pH. Because soil arsenic is fairly soluble and mobile, the higher the dugout pH, the greater the risk that arsenic will desorb from clay particles into the dugout water (Peryea, 1999). For arsenic, the US EPA does give a general soil screening level (SSL) of 0.4 ppm (Hellested, Kulpa, & Waldeck, 2000). The level of arsenic in the soil sample, 5.8 ppm, exceeds this recommendation. On the other hand, the soil lead generally less likely to leach from the clay particles because it has poor mobility in soil, very low solubility (Peryea, 1999). Although the U.S. Environmental Protection Agency[28] set maximum soil lead concentrations for playgrounds as 400 ppm, a limit for the lead in soils near drinking water reservoirs and/or a general SSL was not found (Peryea, 1999).

8.6 Summary of Key Pilot HRF Results

The key results from the pilot HRF at Ghanasco Dam are as follows:

- During this pilot HRF study, Ghanasco Dam turbidities were between 176 and 540 NTU.

- The pilot HRF system removed between 76-84% of the total influent turbidity while its average flow rate stayed within the SANDEC guidelines (54 – 270 mL/min).

- The granite gravel (G) media performed the best and nearly met the target of reducing the turbidity to < 50 NTU by removing 84% of the influent turbidity (128 - 313 NTU) and producing an average effluent turbidity of 51 NTU.

- The average effluent value for the granite gravel (G), local gravel (D), and broken pottery (P) was 61 NTU, which almost reached the target of < 50 NTU for SSF.

- Laboratory settling tests showed about 30% of the turbidity in the tanks settled while data from the pilot HRF showed approximately 57% of the turbidity settled.

- Settling tests showed that the particle removal mechanisms in HRF were responsible for 46% of the turbidity removal in the granite gravel (G) tube and 30% and 19% turbidity removal for the local gravel and broken pottery respectively.

- The filtrability and sequential filtration tests showed that the majority of particles left in the HRF effluent are colloidal and small supracolloidal particles that do not easily settle.

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[28] Lead; Identification of dangerous levels of lead; Final Rule, 40 Congressional Federal Register Part 745.65(c), January 5, 2001.

9.0 Discussion of Dam Water Quality and Pilot HRF Results

In the context of resource-limited countries such as Ghana, a system like HRF might effectively pre-treatment highly turbid surface water for SSF because it is effective, inexpensive, built with local materials, and easily operated. One of HRF's greatest strengths is the fact that it does not require coagulant chemicals. Eliminating the need for the community to purchase and dose coagulants improves the chances of the system being operated and maintained in the long-term. In addition, the low head loss means very little head is required so there are low energy requirements making HRF a viable option for flat terrain where a gentle slope between the source and the filter allow gravitational flow of water through the filter.

9.1 Dam Physical Particle Characteristics and HRF Design Considerations

Levine et al. (1985) in their work on wastewater treatment argue that understanding how water's particle size distribution is affected by a treatment process can lead to innovative solutions. The same is true for dugouts in Northern Ghana. Collection of source water quality data is essential not only in designing a treatment option, but also in the important prior work of selection and protection of a water source. Protection of the water source from particulate and microbial contamination could be a much more cost-effective option than water treatment or treating the resultant cases of diarrheal illness. Understanding the size and behavior of particles in dugouts can help lead to better, innovative treatment and to practical policy decisions concerning the management and protection of dugouts as water sources.

Beyond the applicability of HRF for low-income countries, the more important measure of its success is the consideration of each HRF's effectiveness at removing suspended matter. Roughing filter design most often fails when the raw water quality characteristics are not well defined. The pilot tests described in this thesis were not conducted to make specific design modifications, yet there was recognition that filter efficiency is strongly influenced by overall raw water quality.

If HRF is to be implemented as a pretreatment step for highly turbid water prior to SSF in NRG, the dugouts' raw water characteristics must be better understood. Lack of data on the characterization of raw water sources in Northern Ghana will continue to be a challenge to engineers designing pre-treatment options. Dams with particles that do not settle out in two days should be considered for a pretreatment method such as HRF because by simple sedimentation in a dugout or in a household's clay urn not enough turbidity will settle out to make the raw water suitable for SSF let alone for chlorine, UV, solar, or other disinfection. Those dams with turbidity from colloidal and supracolloidal particles that don't settle well, like Ghanasco Dam, are good candidates for an infiltration gallery or HRF.

Data from one day during the dry season, though helpful is not representative of seasonal variations. To be more certain of identified trends, more samples from more dugouts and multiple tests of the same sample are necessary. If more extensive studies were done on dugouts in Northern Ghana, the dams could be classified on their location, size, and volume and how quickly they dry up, the population they serve, their seasonal turbidity levels, particle size distribution, and source protection methods. Donor and governmental agencies and nongovernmental organizations could then use this classification to coordinate their efforts to prioritize and plan interventions in a calculated, strategic manner.

9.2 Evaluation of Ghanasco Pilot HRF Design

The pilot HRF produced promising results however future HRF pilot studies' design can be improved and cost reduced. For example, one 700L polytank can be used instead of two. The system could also be located inside a family compound or inside a school's fenced-in property to eliminate the expense of paying a 24-hour watchman. Such a system can be reused and transported to complete pilot HRF studies in different communities.

9.2.1 Variable Flow Rates

Flow through the HRF pipes may have been impacted by unseen air bubbles present because of uneven ground. Sample ports drilled into the PVC pipe where the media gradation changed showed that one air bubble was present at the start of the P tube (Figure 68). The pilot HRF should be built on level ground. A straining screen would help reduce clogging by debris and live organisms sometimes get fed into the filter (Figure 68).

Figure 68 Pilot HRF maintenance: fish found in ceramic filter (P) (left) and author removing air bubbles (right)

The flow rate was difficult to regulate. The average G, D, and P flow rates, 218, 167, and 194 ml/min respectively, are higher than values Wegelin recommended 54–108 ml/min (0.4 – 0.8 m/h) to effectively remove colloidal particles (Wegelin, 1996). Variable flow rates in the pilot HRF system results made it was difficult to compare results of the G, D, and P tubes. The sticky valves made it challenging to maintain constant flow rates. In place of the valves, a flow regulator should have been used. Figure 69 and Figure 70 show a possible design taken from the design of a chlorine floating doser commonly used in Central America and elsewhere.

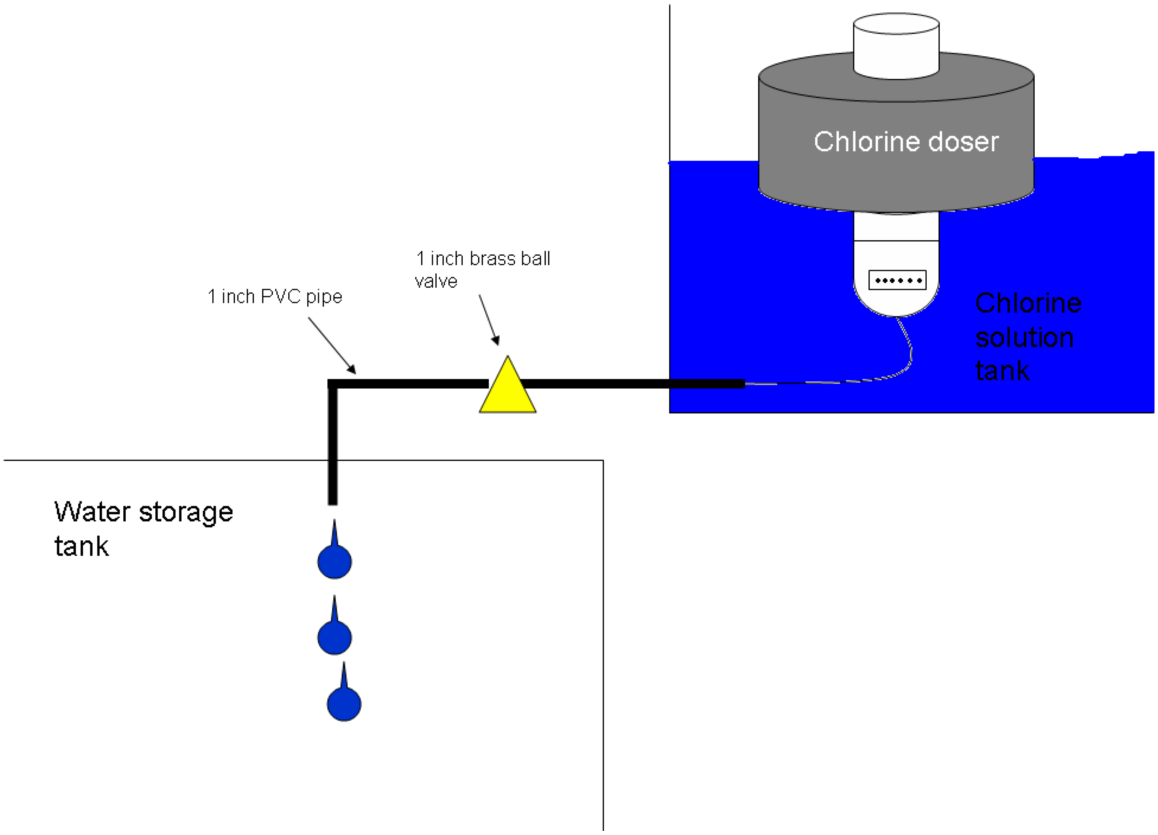

Figure 69 Chlorine dose-regulator design from El Salvador, Central America

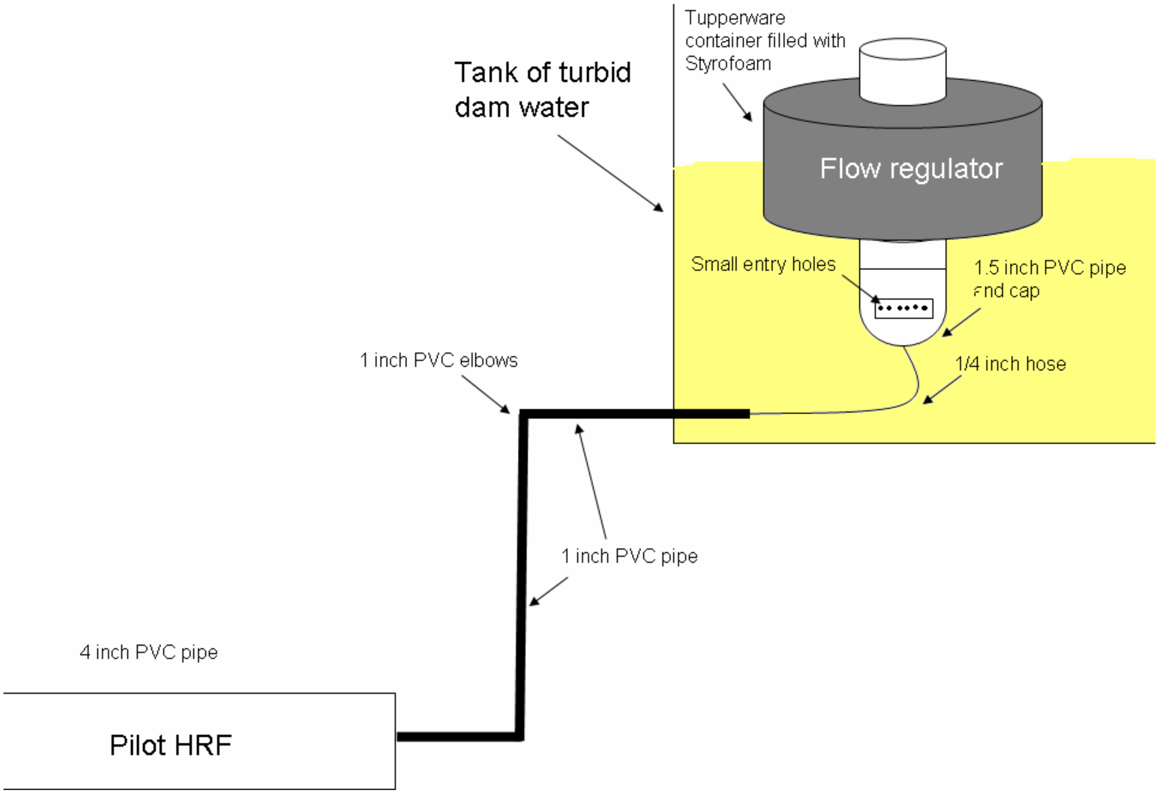

Figure 70 Idea for flow regulator for pilot HRF system

9.2.2 Short Circuiting along the Pipe Edges

Another improvement to the pilot HRF system would be to use PVC tubes with wider 10” or greater diameters to prevent the occurrence of side-walling. Alternatively one could build the HRF in a dug and plastic tarp-lined trench. Collins from the University of New Hampshire indicated that the pipe diameter in a HRF pilot test should not be less than 10” because a smaller pipe diameter can cause sidewall short-circuiting in pilot filters so that the flow takes the path of least resistance, all together missing the roughing media[29] (Collins et al, 1994). Although the 4” HRF tube diameter did not adhere to Wegelin’s recommendation of having d_{column}/ d_{media} = 25, he also indicated that this ratio could be reduced for HRF because the media is not as densely packed along the walls (Wegelin, 1996). However, it is not clear how much the ratio can be reduced. Table 21 shows that increasing the pipe diameter to 10” would greatly improve the ratio. For a 10” pipe, the ratio will only be below 25 in the third section, dp_3 (marked with ***).

Table 21 Comparing Short-Circuiting Ratios with Pipe Width

Short circuiting ratio	**cm**	**d_{column}/ d_{media}**		**Cm**	**d_{column}/ d_{media}**		**cm**	**d_{column}/ d_{media}**
Diameter of pipe	10.2 cm or 4”			25.4 cm or 10”			152.4 cm or 60”	
Dp$_1$ media	0.60	16.9		0.60	42.3		0.60	254
Dp$_2$ media	1.00	10.16		1.00	25.4		1.00	152.4
Dp$_3$ media	2.50	4.064		2.50	10.16***		2.50	60.96

9.3 Ghanasco Pilot HRF Turbidity Removal

Turbidity results from this study showed that after ripening for 52 days a HRF using granite gravel can achieve high separation rates for colloidal particles and remove 84% of suspended matter from highly turbidity raw water. One of the most important results from pilot HRF at Ghanasco Dam is that, on average, gravel roughing media was able to remove 61% of turbidity from a tank (128-313 NTU) producing an average turbidity effluent of 51 NTU. This is a conservative value because it assumes that some suspended particles in the tanks have settled out before flowing into the HRF tubes. Furthermore the tank turbidity samples were taken at the top of the tank when the actual inlet to the HRF tubes was at the bottom and probably fed more turbid water into the HRF tubes than the average tank value implies. The HRF’s turbidity removal capacity should improve as the filter continues to ripen and fills with sediment.

Although only two settling tests were conducted for the HRF tanks and effluents, the average percent removal of turbidity from colloidal particles is promising. The results from the filtration and settling tests showed that non-settleable particles contributed to approximately half of the influent turbidity. In Figure 63, the high percent of turbidity removed between the settled tanks’ and media’s turbidity values shows the HRF’s effectiveness at removing turbidity. The results for the settling test highlight biofilm formation, ripening, and settling as important particle removal mechanisms. For the

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[29] Collin’s recommendation of using a pipe of 10” or larger for RF pilot studies come from a five-month pilot study of medium sized gravel (5.5 mm) HRF in Texas City, USA. The filter was able to remove 47% of total bacteria and 37% of raw water algal cells (Collins, Westersund, Cole, & Roccaro, 2004).

broken pottery (P), small clay particles being broken off from the broken pottery and re-suspended in the filter flow could have been the cause of higher and less settleable effluent turbidities.

To truly show the HRF's effectiveness at turbidity removal, multiple settling tests need to be done on each set of samples and the pilot test must run for a longer period of time that spans the months where dam turbidities reach their maximum levels during the rainy season and minimum during the dry season. There could be even better turbidity removal if the media were given more time to ripen with biofilm and if the flow rate were kept between 54 – 108 ml/min. In lowering the filtration rate, the challenge is to produce enough drinking water to satisfy the ever growing demand.

9.3.1 HRF Ripening

Roughing filters might remove clay particles more effectively if the filter were ripened longer. At the end of 52 days, it is probable that some type of slimy, biofilm layer had formed around the media pieces but it might not have reached its maximum turbidity removal capacity. However, closer inspection under a microscope would have showed for sure. One difficulty in relying on biofilm removal of turbidity is that it is difficult to test when a filter is ripened and to know exactly how long the filter takes to ripen. It is also easy to flush the biolayer out of the system by accidentally increasing the flow rate. A typical time period for a pilot test is 150 to 365 days (Wegelin, 1996). It would be interesting to determine the algal content of Ghanasco Dam water because Collins found that RF remove clay particles more effectively when a filter was ripened with algal cells (Collins et al, 2001).

9.3.2 Comparison of Ghanasco Pilot HRF Performance with other HRF Systems

Despite HRF's technical success at producing water with lower turbidity, some of the colloidal particles in the effluent that are most likely clay particles are still too small to settle. There are limitations to HRF which depend on the treatability of the raw water and the media properties. Wegelin, for example, wrote about a case in Peru where the community had to use aluminum sulfate and to adjust the raw water pH to 10 with lime in order to remove the stable suspension of colloidal material (Wegelin, 1996). Our goal was to see if, without the addition of chemicals or mechanical equipment, a HRF could remove enough turbidity to make SSF feasible in Northern Region, Ghana.

Table 22 presents a comparison of the performance results from the Ghanasco Dam pilot HRF, a 2-month long, HRF pilot study from the International Institute for Water and Environmental Engineering in Ouagadougou, Burkina Faso (Sylvain, 2006) (Figure 71), and a HRF study completed by the Blue Nile Health Project in Sudan (BNHP) (referenced by Wegelin, 1996).

Figure 71 International Institute for Water and Environmental Engineering HRF pilot study (June 5 - July 28, 2007), Ouagadougou, Burkina Faso (Sylvain, 2006)

The Ouagadougou system had a very low mean turbidity removal rate of 32% in comparison to the pilot HRF system at Ghanasco Dam which showed mean turbidity reductions between 76-84%. In light of the low turbidity of the raw water feeding the Ouagadougou system from Loumbila Dam, the capital's drinking water source, this low mean turbidity is not so alarming. Given a similar range of raw water turbidities, it is more fitting to compare the Ghanasco Dam pilot HRF to the BNHP. Indeed, the BNHP results mirror the results from this Ghanasco Dam pilot study quite closely because in both cases the gravel media exceeds the broken burnt bricks/broken pottery in mean turbidity reduction. Both have mean turbidity reductions of about 80%, but the BNHP has an average filtration rate that is about five times slower than the Ghanasco Dam pilot HRF. This suggests that if the average filtration rate at the Ghanasco Dam HRF were greatly decreased, there would be an even greater turbidity reduction.

Figure 72 Location of HRF pilot system in Ouagadougou, Burkina Faso https://www.cia.gov/library/publications/the-world-factbook/geos/uv.html

Table 22 Comparison of Ghanasco Dam pilot HRF with other HRFs

	Blue Nile Health Project, Sudan referenced by Wegelin, 1996)		**Ghanasco Dam, Tamale, Northern Ghana Pilot**** (Losleben, 2008)			**Ouagadougou, Burkina Faso Pilot** (Sylvain, 1989)
Media	broken burnt bricks	gravel	granite gravel	local gravel	Broken pottery	quartz gravel
Average filtration rate (m/h)	0.30		1.6	1.3	1.5	1.0
Filter length and media size (mm)	270 cm, 30-50 85 cm, 15-20 85 cm, 5-10		350 cm, 12-18 250 cm, 8-12 100 cm, 4-8			400 cm, 15-25 150 cm, 5-15
Raw water turbidity	40-500 NTU		220 NTU	218 NTU	218 NTU	5-50 NTU
HRF effluent water turbidity	5-50 NTU		51 NTU	72 NTU	61 NTU	4-19 NTU
Faecal coliforms* (/100ml)						
Raw water	> 300	---	8375	8375	8375	---
Prefiltered water	< 25	---	---	15500	500	---
Mean turbidity reduction	77 %	87 %	**84 %**	**76 %**	**80 %**	32 %

* as *E. coli*

**Turbidities were initially measured as TU and converted into NTU using the correlation in Appendix D: Relationship between Nephelometric Turbidity Units (NTU) and Turbidity Units (TU).

10.0 Channel Horizontal Roughing Filter Design Based on Pilot Study Findings

Thus far, HRFs in Ghana in Zabzugu, Salaga, Mafi Kumase, Mafi Zongo, and Chirfoyli and have all been designed for a pumped distribution system. The addition of a pump to the treatment process greatly increases the capital, O&M costs, and skill required for operation and maintenance. Designing a HRF to fit in a long, cement-lined channel that would gradually transport the water by gravitational flow from the dugout, through the channel HRF and SSF treatment, and into a partially sunken cistern equipped with a rope and washer pump would eliminate the need for a pump.

10.1 Kunyevilla Dam Channel

Kunyevilla Dam was visited to inspect a long, cement-lined channel that may have been designed as a channel HRF. Though some large gravel pieces were found in of the sections near the cistern and another cover portion of the channel closer to the cistern was described as containing sand, it was uncertain whether the Kunyevilla Dam channel was designed to be a HRF-SSF system (Figure 74). In any case, the channel was in a state of disrepair. Many of the concrete slab channel covers had been removed. The dugout's water level was low and water was no longer entering the channel. There was dirty, stagnant water and dead frogs in the channel. Figure 73, Figure 74, and Figure 75 show multiple views of the Kunyevilla Dam channel. Before designing a channel HRF, it is important to learn from past mistakes at Kunyevilla Dam and to consider the application of insights from the present study to the on-the-ground reality of improving water quality at Kunyevilla Dam.

Figure 73 Kunyevilla Dam in the rainy season (left) and dry season (right)
Photo Credit: Kelly Doyle (2007) (left)

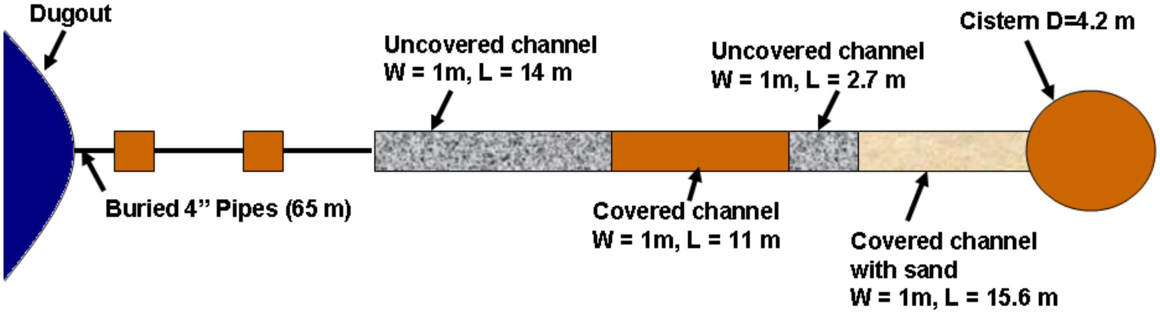

Figure 74 Kunyevilla Dam channel dimension, near Tamale, Northern Ghana

Figure 75 Kunyevilla Dam channel in the rainy season (left) and dry season (center and right)
Photo Credit: Kelly Doyle (2007) (left)

Figure 76 Kunyevilla Dam cistern and channel in the rainy season (left) and the dry season (right)
Photo Credit: Kelly Doyle (2007) (left)

Figure 77 Cistern (left) and rope and washer hand pump (right) in the rainy season at Kunyevilla Dam, near Tamale, Northern Ghana
Photo Credit: Kelly Doyle (2007)

10.2 Classical Filtration Theory

To accurately compare the HRF filters' turbidity results filter coefficients λ were calculated to take into consideration the variability of the flow rates. Wegelin explains that the "filter coefficient λ is a function of the interstitial flow pattern (depending on filtration rate and pore size distribution), of the grain surface area (depending on size and shape of the filter medium) and of Stoke's law parameters of the water and the suspended particles (particle size, density)." (Wegelin, 1996) A HRF can be designed once the filter coefficient has been determined for a given media and water source.

Classical filtration theory proposes an exponential relationship between the effluent turbidity (T) divided by the influent turbidity (T_0) as Equation 1:

Equation 1 $(T/T_0) = \exp(-\lambda * \tau)$

λ is the filter coefficient. τ symbolized the residence time.

The filter coefficients for each filter media (G, D, and P) are plotted using Equation 2 in Figure 78:

Equation 2 $\ln(T/T_0) = -\lambda * \tau$

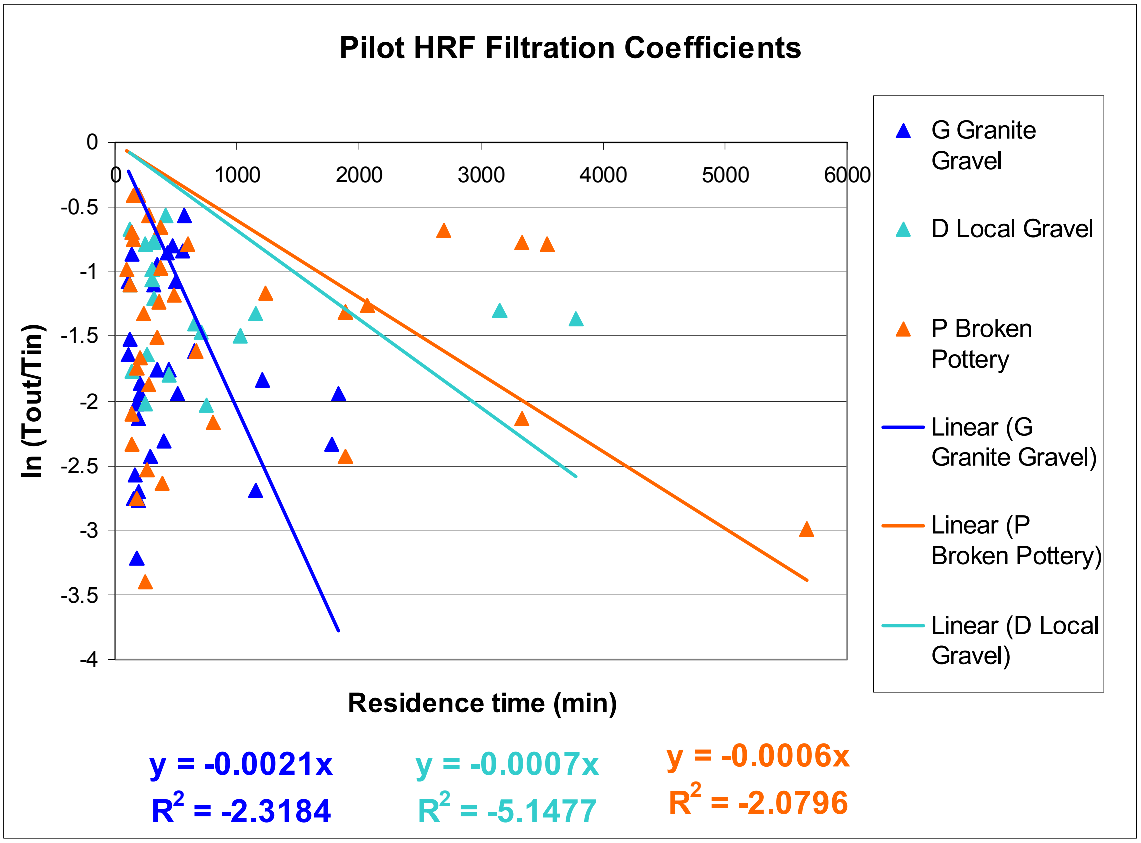

Figure 78 Finding the filtration coefficients for the pilot HRF at Ghanasco Dam

10.3 HRF Channel Design for Ghanasco Dam

Using the filter coefficient calculated for the granite gravel (G), the best performing HRF media, a basic design was applied to a hypothetical channel HRF at Ghanasco Dam. A number of assumptions were made:

• Beneficiary population	10,000 people
• Water demand	7.5 L/pp/day Q = 75,000 L/d or 3.12 m3/h
• Rainy season dugout mean turbidity	T = 700 NTU
• Flow rate	q = 1.6 m/h
• Cross-sectional area	A = 1.95 m^2
• Depth	z = 1 m
• Width	y = 2.m

The length of the channel HRF was determined by varying the length (x) of the channel until the effluent turbidity, $T_{0,}$ reached 20 NTU. The channel has the same proportions of large (50%), medium (36%), and small media (14%) as in the Ghanasco Dam pilot test. The result from these calculations can be seen below in Figure 79 and Figure 80.

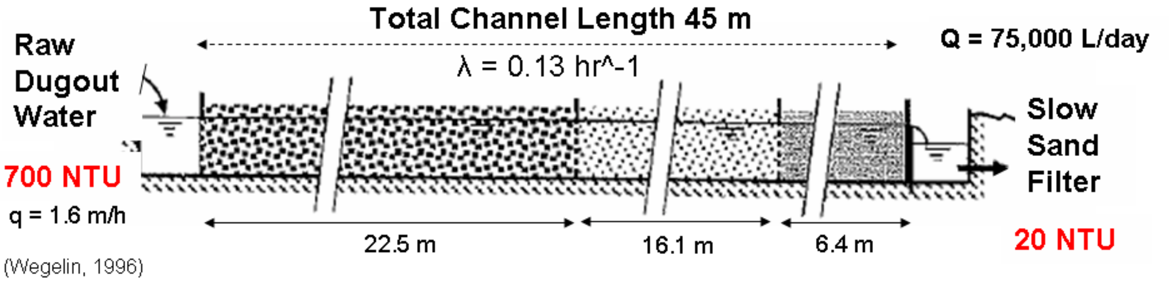

Figure 79 HRF channel design based on granite gravel filtration coefficient, side view (Wegelin, 1996, Section 10.4 & Annex 4-4)

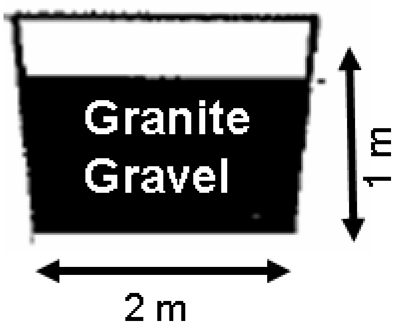

Figure 80 Ghanasco Dam HRF channel design cross-section (Wegelin, 1996)

Surprisingly the design length of the HRF channel, 45 m, is very close to the actual length, 44m, of Kunyevilla Dam channel. This suggests that the Kunyevilla Dam may have been initially designed as a HRF.

Apart from technical design considerations, before this channel HRF design is considered appropriate, the process of participatory community planning and development around source protection, water use, water treatment must be started and its total costs must be calculated. Given its inexpensive cost and flexible design, variations of HRF have been implemented in Sudanese refugee camps using earthen trenches lined with impermeable plastic. If a very strong plastic tarp were found, this could be a cheaper option in rural areas of Northern Ghana. It would also be wise to complete a cost-benefit analysis and multi-objective or sustainability analysis of other community-based treatment options for highly turbid water, such as boreholes or coagulation. Completion of a baseline health survey before implementing the project and some time after the intervention would allow conclusions to be drawn on the HRF-SSF system's impact on reducing the disease burden of diarrheal disease.

11.0 Case Study of HRF at Mafi Kumase, Volta Region

During the mid 1990s, a number of HRF-SSF multi-stage filtration systems were introduced to Ghana as part of SANDEC's surface water treatment program for RF pilot projects in rural areas headed by Martin Wegelin and supported by an excellent team of local Ghanaian engineers including Afrowood Consulting Ltd. led by Dorcoo Kolly from Mafi Kumase in the Volta Region of Ghana. The assumption was that HRFs would provide adequate pre-treatment of turbid surface water and in turn make SSF a viable option for drinking water treatment. Pilot tests were conducted and the first HRF-SSF in Ghana was built in Mafi, Kumase, a rural community with a population over 10,000 people in the Volta Region near Togo. Subsequently, other RF-SSF systems, at Zabzugu near Yendi, Salaga in the Northern Region, and Mafi Zongo in the North Tongu District of the Volta Region. Currently, HRF are in:

- Zabzugu - The Zabzugu system was designed and built by Afrowood Consulting Ltd., Accra, Ghana; it is the largest HRF-SSF system in Ghana. It is based on a dam catchment and includes prefiltration, upflow RF, SSF, and chlorination. Unfortunately, the Zabzugu water source, a dam, dries up during the dry season making the system usable for only part of the year.

- Chirifoyili - Recently, UNICEF began construction of a HRF-SSF system at the Chirifoyili Dam; however the construction was suspended due to budget difficulties (Figure 81).

- Kunyevilla - Kunyevilla Dam was also visited and had a broken-down canal structure that could have been the remnants of a channel HRF-SSF. Apparently Taysec Construction Company enlarged the Kunyevilla Dam in April 1997 but it was Village Water, a local Tamale-based NGO, that actually built the channel system, cistern, and rope and washer pumps (see Section 10.1)

- Damongo - There is also an upflow RF in Damongo, Tamale that was built by Ghana Water Company Ltd.

- Mafi Zongo - There is another upflow RF in Mafi Zongo, Volta Region built by Ananda Marga Universal Relief Team (AMURT), an Indian NGO.

This chapter will specifically focus on the Mafi Kumase HRF-SSF system because it has been in operation for over 20 years and carries a strong tradition of good operation and maintenance (O&M) coupled with an excellent community organization structured.

Figure 81 UNICEF HRF in construction at the Chirifoyili Dam, Northern Region Ghana
Photo Credit: Jen Christian-Murtie, 2007

11.1 Background

The main water source for Mafi Kumase and 16 surrounding communities is the Mafi Kumase impounding earth dam which was constructed in 1970 by the Government initially for irrigation (Figure 11). Dorcoo Kolly, an engineer from Mafi Kumase that worked with Martin Wegelin to design and set-up the HRF-SSF system reported that the dam water could sometimes reach turbidities as high as 148 NTU (110 TU) in the wet season and in the dry season as low as 9 NTU (7 TU) (measured January 2008). Even the highest turbidity values for Mafi Kumase Dam are low in comparison to the water from Ghanasco Dam near Tamale (Northern Ghana) whose low turbidity values averaged 304 NTU (225) TU in the dry season. The Mafi Kumase HRF-SSF system caretaker, Perry, reported that the dam was originally a water course that was dug out and dammed to form the current reservoir. Guinea worm, bilharzias, and diarrhoeal disease were prevalent before the water was treated. As a result of the safe quality of HRF-SSF treated water combined with water and hygiene education, and community campaigns, Guinea worm and bilharzias have been eliminated from the area and diarrhoeal disease greatly decreased. Unfortunately, the health impacts of this implementation were not recorded. However Dickens Asafo, the first Caretaker and Community Trainer and a local resident of Mafi Kumase recounts that after six months of commissioning the plant, the numbers of cases of Guinea worm, bilharzias, and diarrhea were greatly reduced. After one year, Guinea worm and bilharzia were completely eliminated. People still have scars from Guinea worm but there are no more cases. This success case is drastically different from that of Northern Region Ghana where the Carter Center and many other organizations since 1986 since have spent millions of dollars to try to eradicate Guinea worm disease from what is known as the Guinea-worm-capital of the world.

11.2 Design and Construction

The Mafi Kumase HRF-SSF project took three years to plan and construct from 1983 to 1986. The first year was spent planning and designing the system and developing the community's water management structure. Construction of the actual filters and the distribution systems took two years. Initially the system was designed to serve 6,000 people through communal standpipes. Today the system has 70 taps and services more than 11,000 people in 17 communities. Water is pumped twice a day to fill two reservoirs with a total of 150 m^3 however this is not enough. The consumption rate was initially about 800,000 L/d when there was just one 80 m^3 reservoir. Then they added another 70 m^3 reservoir in 1997, about ten years later. The demand for water grows as the local population grows and nearby communities want to benefit from the treated supply of water at Mafi Kumase[30].

Figure 82 View of Mafi Kumase from the elevated water tanks

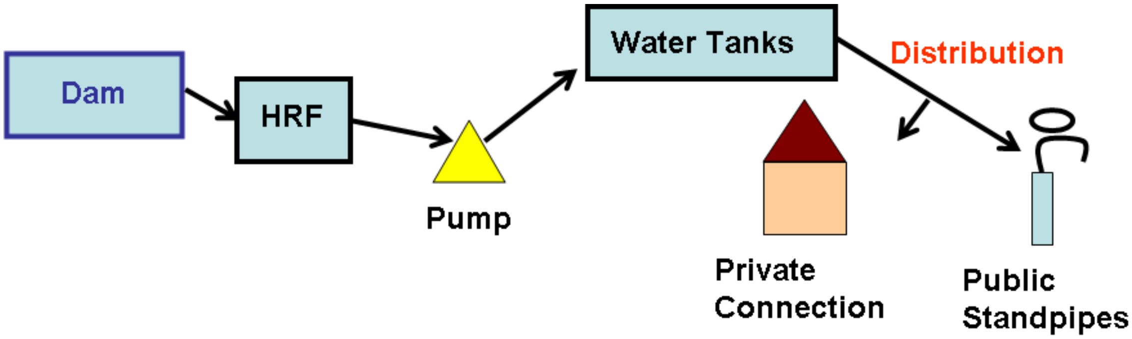

Figure 83 Diagram of Mafi Kumase water system

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[30] Perry, the Mafi Kumase HRF-SSF caretaker estimates that currently one person collects four 34 L buckets a day for a household.

Figure 84 Raw water from the Mafi Kumase reservoir (7 TU) (left) and Ghanasco Dam water from G tank (216 NTU) (right)

Unlike dam water in Northern Ghana, the surface water in Southern Ghana has much less suspended particulate matter. The visual contrast in Figure 84 is dramatic.

Figure 85 Mafi Kumase HRF: dirty gravel media (left) and view of HRF from the inlet (right)

The Mafi Kumase HRF-SSF system had infiltration pipes at the bottom of the dam that moved water by gravity flow to the treatment plant. The HRF-SSF system was designed in two parallel lines that could be alternated if one line needed to be cleaned. During construction local materials and unskilled and skilled labor (steel, plumbers, and carpenters) were used when possible. Community members collaborated in the construction. The gravel came from Tema about 100km away. Full cleaning of the HRF media, a laborious task, is done voluntarily by the community approximately every three to six months. Hydraulic cleaning could be done more frequently to maintain the system running efficiently. The majority of funding for the $300,000 system came from the

Swiss Caritas[31] and contributions from the partner Swiss town of Elgg, the town of Zurich, and some individuals from Switzerland. The community itself contributed GHC1 ($1) per male and 50 GP ($0.50) for the procurement of local materials, payment of allowances to artisans and additionally undertook all skilled and unskilled labor required in the construction phase.

Figure 86 Perry, the author, and Dickens in front of the Mafi Kumase water tanks

After flowing through the HRF and SSF, the water is pumped to water tanks situated at the top of one of the few hills in the area (Figure 86). Then the water is distributed by gravity to communal standpipes and a few private taps (Figure 87). Initially, there were to be no household connections as having access to water at home normally increases the quantity of water used, increases the cost of pumping, and could deplete the available dam water source. However there have been some exceptions. Although the construction cost for a HRF-SSF pumped system is higher than conventional systems, the maintenance costs are lower and the easier maintenance is less complicated than conventional systems.

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[31] Caritas International is a conglomeration of 162 Catholic relief, development, and social service organizations that was founded in 1987 and works to improve the lives of the poor and oppressed in over 200 countries and territories (www.caritas.org).

Figure 87 Mafi Kumase water standpipe and private tap

11.3 Operation and Management

One of the most impressive components of the Mafi Kumase HRF-SSF system is that it has been operating for the last 20 years. In light of the low sustainability record of most rural communal water systems, there is a wealth of knowledge to learn about how this medium-sized, rural community has operated and managed the system.

From the onset of the project through the implementation, the community elected a Town Development Committee (TDC). Early in the project planning process, the TDC elected a Water Project Committee that was responsible for the mobilization of the citizens. People with skills were elected to serve on a voluntary basis as chairman, treasurer, and secretary. Additional committees were formed such as the implementation committee comprised of the headmen of each of the surrounding villages captured in the network, the Youth Committee, and Water and Sanitation Committee. Other important participants in the TDC were the Women Leader, the Queen Mother, and the other Opinion Leaders. An important responsibility of the TDC was to decide tariffs, how to charge for water, and set a fee structure based on the calculated costs of running the system. For this, the TDC received financial training from Mr. Dorcoo. From the TDC, two paid caretakers were chosen and technically trained to run and maintain the system. Part of the training consisted of water quality testing that included all of the physical water quality tests developed by SANDEC and described in Section 6.0. While the influent and effluent water quality might have been rigorously tested during the inception of the system, after 22 years, Perry, the caretaker did not have the original physical water quality testing equipment or system performance records so one assumes that water quality testing was discontinued some time ago.

Dickson Asafo, a leader from the community, was the first to be trained by Martin Wegelin on how to operate and manage a HRF plant. He later became the head trainer and traveled throughout Ghana to advise others as new systems were built. Another undeniable resource and guardian for Mafi Kumase has been Dorcoo Kolly, a Swiss-trained engineer originally from Mafi Kumase. He has years of experience working on water systems and continues to help solve these rural communities' water supply and quality challenges both nationally and in his town of Mafi Kumase.

11.3.1 Mafi Kumase Physical Water Quality: Filtrability Test

Only one physical water quality test, filtrability was performed by the author at Mafi Kumase because of time constraints. As explained in Section 6.2.2, this test measures the amount of water that is able to filter through a 1.5µm polycarbonate capillarpore membrane Hach® filter after 1, 2, and 3 minutes. If more water is able to flow through the filter paper this shows there is less suspended matter in the water.

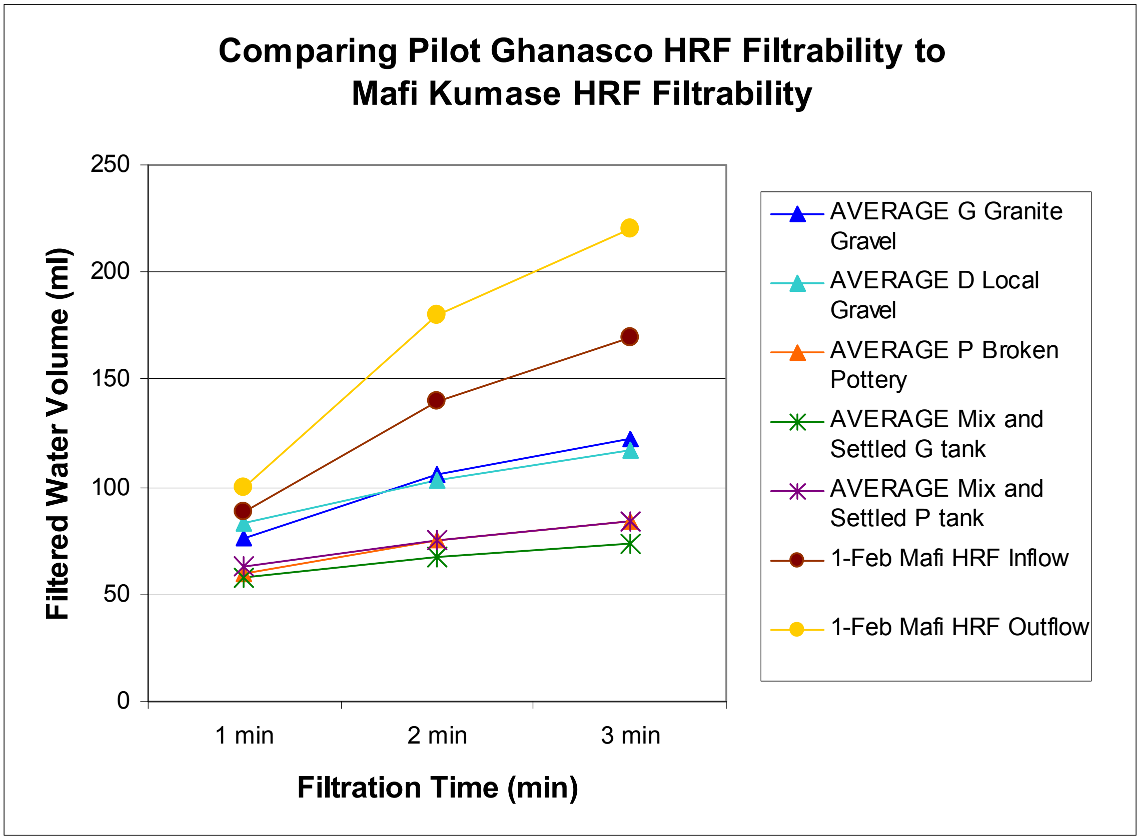

Figure 88 Filtrability comparison between Mafi Kumase HRF and Ghanasco Dam pilot HRF (January 2008)

Figure 88 compares the filtrability at the Ghanasco Dam pilot HRF in the Northern Region with the Mafi Kumase HRF. It shows that the cleanest water in terms of suspended particles was the Mafi Kumase HRF outflow followed by the Mafi Kumase HRF inflow. This is not surprising because the raw surface water in Southern Ghana seems to have much few suspended particles than Northern Ghana. For this Ghanasco pilot HRF sample, the G and D tubes performed best yet still fall short of the Mafi Kumase HRF. Perhaps if the media's biofilm were allowed to ripen longer, then the Ghanasco pilot HRF would be able to remove more turbidity and its filtrability would be more like Mafi Kumase's.

11.4 Maintenance of HRF

Perry's philosophy on HRF cleaning and maintenance was that "If you have a farm and you don't weed it, it will become bushy." Numerous cleaning schemes were tried over the years. First the responsibility of cleaning the HRF rotated between the 13 communities. There was sometimes not enough participation so instead the TDC collected an extra fee to pay for the cleaning. Dickson described how at first the community was willing to work but now they are less willing. They don't want to do voluntary work. Basically maintenance of public facilities in Ghana is poor because of the people's attitude toward maintenance. Most recently, they have returned to rotational communal cleaning.

Cleaning the RF media is very labor intensive and takes six days when about 20 to 30 community volunteers participate. The gravel is removed with a shovel, added to a barrel full of water, and stirred. This needs to be done every three to six months depending on the level or turbidity in the raw water. Hydraulic cleaning every three weeks helps extend the HRF run times.

11.5 Water Fees Model

The evolution of water fee systems at Mafi Kumase shows how the community leaders have tried to finance centralized, rural water treatment in a sustainable manner. At the beginning, the TDC was afraid to collect and manage money because they would be held accountable by the communities and could be the object of criticism. However, with time and training, they developed a budget for the system's operation and management and from that set up a water fee system. Many community members were astonished that they were expected to pay for water and then go clean the media.

The system operation costs were kept to a minimum but the most expensive part is the electricity bill for the pump. The night watchman and caretaker (Perry) had low-paying jobs. Perry became an important figure in the community as people began to value water more; the community built him a 2-room house with electricity beside the treatment plant and gave him a bike to facilitate his work.

To cover these costs, the TDC started charging a set water fee of 3.5 GHC per household but changed to pay-as-you-fetch (the human-meter) because of the disparity in household water use. The new commission vendor system developed as well. The TDC found that the system worked better if there was a middleman, a headman, responsible for paying the TDC flat fee per standpipe. The vendor at each standpipe would still regulate pay per bucket but her commission would be 20% of the water sales she made (Figure 89). The water prices are described in Figure 90. Ultimately, the TDC's goal was to collect 42 GHC from 12 neighboring communities monthly. Unfortunately this budget still doesn't meet the operational costs and the pumped water supply does not satisfy the water demand.

The TDC's current idea is to introduce water meters to monitor the water usage at each standpipe tap to better monitor how much water the vendor is selling and keep her accountable. Right now they believe the vendor is selling a lot of water and not accounting for it. While water rules are decided at the TDC's meetings, they need to collect 4500 GHC per month to cover all of their costs. With water meters at each tap they could charge consumers the actual cost of what it took to treat and distribute the water and still make a reasonable savings. Private houses would be charged a higher fee. Unfortunately, water meters are expensive and the TDC estimates they would need 25 which would cost about 600 GHC. Their next challenge will be to raise these funds.

Currently a special System Review Committee has been inaugurated; it is comprised of Mr. Dunyo, a Community Development Specialist and Worlanyo Siabi, a Water Supply Engineer and headed by Kolly Dorcoo, the TDC Projects Consultant. The Committee is assigned to review the entire scheme and its operational structure and recommend strategies which would address the current challenges. The three Committee members are citizens of Mafi Kumase who are engaged in the rural water sector.

Figure 89 Mafi Kumase locked tap (left), standpipe water vendor (center), 34 buckets in use (right)

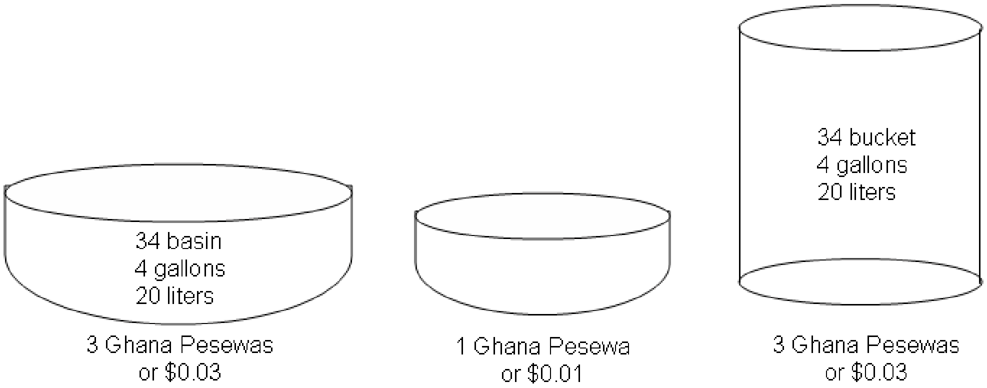

Figure 90 Mafi Kumase vendor water prices

11.7 Future Plans

The TDC plans to make two improvements to the Mafi Kumase water system to better meet the surrounding communities' demands for safe water. In addition to the aforementioned water metering plan, Dorcoo Kolly is leading an effort to greatly extend the system to even more communities by supplementing it with the Volta River as the new supply source from some 35 km away from Mafi Kumase. The HRF-SSF scheme had such a positive impact on the health of the users because it provided adequate quantities of good quality drinking water that consumers from surrounding villages sought to use more water. The Mafi Kumase Reservoir simply is inadequate to store enough water for the area as the population grows and more and more partake in the limited supply.

Nearby, in the town of Zongo also located in the Volta Region, an upflow gravel filter in series (UGFS) and is in operation however it has short filter-runs and requires frequent cleaning. The Zongo system serves about 33 communities. It does not effectively remove turbidity from the raw water because the upflow height is too short for the suspended particles to adhere to the media. The implementers plan to build a HRF. The flat topography means that this system must use a diesel pump to distribute the water to standpipes throughout the communities.

One strong advantage that these communities have over others in the North is the presence of Dorcoo Kolly as highly educated engineer from the area willing to guide and support the communities as they seek to meet their basic need for water.

12.0 Challenges with Community-Based Water Systems Management

The technical operational and maintenance problems of water systems can be identified and rectified, but if there is not a working framework and commitment on the part of the community and other stakeholders, the management of the water system becomes the frail breaking point of the system. Political, economic, cultural, and organizational aspects of water systems management are critical components in the overall sustainability of the system and are beyond the scope of this thesis. This section simply addresses one key aspect of systems sustainability, cost-recovery, which is one of biggest challenges facing communities seeking to operate and maintain centralized systems.

12.1 Cost-Recovery

Among the biggest challenges for communities relative to their safe drinking water supply are people's unwillingness to pay, mismanagement of funds, and corruption. These impact the sustainability of community water systems because they inhibit cost recovery. From a sustainability perspective, one of the most problematic aspects is developing fair, realistic, user water tariffs that are actually able to cover the full systems' supply costs. In Ghana, until the late 1990s, most rural communities did not pay user fees for access to water because they did not have access to potable water. According to some traditions they think water is like air and sunlight; it is a natural gift from God that should be accessible and free to all. That belief works well without water treatment but when water treatment exists, cost recovery needs to be a priority even in poor, rural areas of Africa.

Consumer education can gradually dispel the expectation that all water should be free. Just as the universal right to water applies to all, so all who receive water from an improved source should be ready to pay a fee. In poverty stricken areas of Africa, collection of water-user fees is especially challenging as the beneficiaries have limited financial resources and are accustomed to receiving subsidized services instead of their organizing themselves to solve their own water problems. Gyau-Boakye (2001) in his review of the community management of rural groundwater supplies, references an important study on rural cost recovery done by Whittington et al. in 1990 in the Anambra State of Eastern Nigeria. Whittington's conclusions:

- Ability to Pay - Cost recovery efforts have been weak because they assume that people cannot afford to pay very much for water when in fact they are often already paying sizable portions of their income for water.

- Consumer Preference - Though public water authorities try to develop cost recovery schemes, they often fail because they do not adequately understand the beneficiaries' preferences about when they want to buy water, how they want to pay for it, and how much they are willing to pay.

- Flexibility - Whittington's results show that consumers want more flexibility and control over their water expenditures. In other words, they prefer something other than a fixed monthly fee because unexpected medical emergencies and seasonal agricultural expenses are higher priority uses for their limited cash resources.

- Mistrust - Unfortunately the unfulfilled promises of water projects and record of past failures create an environment of mistrust and lack of confidence in the government. As a result, people are only willing to pay a small fee for water until they actually see the complete project and receive water.

13.0 Conclusions

With poor groundwater accessibility, water quantity, quality, and accessibility will become a growing problem and potentially also a source of social tension, conflict, and economic burden in Northern Region Ghana. While millions of donor dollars fund interventions that provide boreholes, one complimentary long-term solution also lies in improving and protecting dugouts. Solutions that grant communities improved access to potable water must be multi-dimensional and focused on developing community ownership and leadership of the project and creating financially sustainable O&M systems, as has been successfully demonstrated in Mafi Kumase.

The first step is to better understand dugout water quality and their physical and chemical properties as water sources. Until this occurs, problems with treating highly turbid water will persist. In turn, as more is learned about the physical water quality of dugouts, HRF and other technologies can be modified to more effectively remove suspended particles from highly turbid waters. For the extremely turbid water in NRG, using design parameters from Wegelin (1996), the best performing media, the granite gravel (G) barely met the target turbidity of < 50 NTU with its average effluent of 51 NTU. The filtrability and sequential filtration results confirmed that the majority of turbidity remaining in the HRF tube effluents was from colloidal (< 1µm) and small supracolloidal particles (< 10µm). Given that this pilot study was run during the dry season when NRG dugout turbidities are typically lower (250 NTU), the results suggest the HRF design needs to be modified further to remove colloidal particles such as clay and to effectively treat more turbid rainy season NRG dugout water (931 NTU) (Foran, 2007).

In this pilot HRF study at Ghanasco Dam, plain settling in the HRF tanks removed an average of 57% of the turbidity, while a laboratory settling test shows about 30% reduction of turbidity through settling. The coarse media in the pilot HRF enhanced turbidity reduction by removing an average of 55% of the turbidity of raw dugout water (average 350 NTU) entering the HRF tubes from the HRF tanks. Out of the three coarse media, granite gravel (G), local gravel (D), and broken pottery (P), the granite gravel media on average removed the most turbidity at 84% turbidity removal and a filter coefficient of 0.002 min^{-1}. The results from the settling test emphasize the importance of HRF in particle removal because, on average, the granite gravel (G) media removed 46% of the initial turbidity, twice as much as plain settling, which removed an average of 25% the turbidity.

Overall, with average 80% turbidity removal and an average effluent turbidity of 61 NTU, HRF has potential as a pretreatment option for the dugouts in Northern Region, Ghana. Therefore, with more investigation of the HRF effectiveness at removing turbidity from even more turbid, rainy seasons dugout water, using SSF could be a viable, low-cost treatment option in a multi-stage filtration system that first treats the raw water with HRF.

14.0 Recommendations

The structure of community-based management and operations of centralized water systems will greatly vary. However the following guidelines are applicable to many situations when choosing a community and project site for a community-scale water system as has be described in this report:

14.1 Choosing a Community

- Community Leadership – From the initial steps, open honest communication between the community and other stakeholders is essential to better understand their needs, culture, traditions, preferences, and capacity to organize and lead.

- Trainability or Readiness - A common problem among NGOs working with water supply in Ghana[32] is that they do not find the suitable people in the communities to train to be system operators (Gyau-Boakye, 2001). The implementing organization and community need to complete an honest assessment to consider if there are some things the community will not have the technical training or resources or willingness and/or organization capacity to do operate and maintain the system. Conversely, there should also be an open discussion about the community's capacity to manage the system well.

- Coordinate Aid Efforts – To extend development aid so it reaches the greatest number of those lacking access to potable water and avoids duplication, aid organizations need to develop and implement a coordinated national and regional plan that targets Ghana's diverse populations and builds on each organizations' expertise. It would be best if local community leaders were also involved in this decision-making, resource allocation process.

- Water Source – Choosing a water source is fundamental in the process of extending water service to a population. The source must provide adequate: coverage, continuity of flow, water quantity, water quality, have a reasonable projected cost, and be within the beneficiaries' management capacity (Galvis et al, 1993).

14.2 Dugout Water Quality

- Dugout Water Quality - An understanding of particle sources and the physical variations in raw water quality with climatic and seasonal variations can aid local leaders in setting good water regulations and planning in how improve and protect dugouts as a water source.

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[32] Water Aid, Oxfam, UNICEF, World Vision International, Catholic Relief Service, and the Adventist Development and Relief Agency are a number of the organizations involved with improving access to potable water in Ghana.

- Soil Concentrations of Lead and Arsenic around Ghanasco Dam: Studies should test soil around Ghanasco Dam and other NRG dams for lead and arsenic. Based on the results, the fate and transport of these particles should be explored to determine if the particles were to reach the dam, whether the rate of settling, deposition, and dissolution of lead and arsenic would cause there to be unsafe levels of lead (< 0.01 mg/L) and arsenic (< 0.01 mg/L) in the dugout drinking water (WHO, 2004).

- Develop Local Watershed Protection Plans - Inexpensive improvements can be made to the periphery and catchment area of the dugout to improve its water quality. For example, planting natural barriers to catch particulate matter in runoff before it enters the dam or digging deeper dams to conserve water by reducing the surface area exposed to evaporation.

- Dugout Water Quality Monitoring – Long-term monitoring of not just the improved water supplies but the surface water and other unimproved sources including all the rural dugouts will create a much clearer picture of their physical water quality, seasonal changes, and long-term trend in water quantity, quality, accessibility, and reliability and how climate change, deforestation, desertification, and changing weather patterns are mpacting the poorest rural populations in Northern Ghana.

- Setting up a Dugout Monitoring Campaign after the Model of the Guinea Worm Eradication Accolades - Partner with trained Guinea Worm Volunteers (GWV), universities and schools and Peace Corps Volunteers (PCVs) to monitor dugout water quality. If provided with some basic, inexpensive lab equipment, the monitors could train the Guinea worm volunteers and team with students to perform simple monthly or bimonthly physical water quality tests similar to those preformed in this study such as turbidity, solids settleability, and suspension stability plus simple microbial testing. The results could be compiled, analyzed, and shared with a central office. Follow-up support must be available to communities whose results show positive microbial contamination and/or especially high turbidity turbid to plan for and implement a source protection and/or treatment intervention.

- Appropriate Standardized Equipment – Procedures for HRF water treatment plant operation and maintenance need to be simple and standardized.

14.3 Horizontal Roughing Filtration Improvements

- Rehabilitate and Upgrade Existing HRFs - Rather than constructing more new HRFs in Ghana, it would be more cost-effective to repair the existing HRF systems, like the channel at Kunyevilla Dam, and work closely with the community to develop better operations and maintenance practices. Preliminary work should focus on community participation together with a local leaders and a technically trained person identifying challenges and solutions. Completion of a baseline health survey before implementing the project and some time after the intervention would allow conclusions to be drawn on the HRF-SSF system's impact on reducing the disease burden of diarrheal disease. This information could be used to do a cost-benefit analysis and comparison between the Disability Adjusted Life Years (DALYs) prevented by a borehole, HRF-SFF system, and coagulation-chlorination system.

- Investigate Media and Particle Properties to Enhance Colloidal Particle Removal - Investigation of the chemical and physical properties of coarse roughing media available in NRG and colloidal particles in the dugout water could lead to the improvement of the HRF design to favor biofilm formation and/or use particles charges and chemical properties to improve turbidity removal removing turbidity.

- HRF Pilot Test during Rainy Season – This pilot study was run during the dry season when NRG dugout turbidities are typically lower (250 NTU) (Johnson, 2007). However, the HRF design needs to be modified further to remove colloidal particles such as clay and to be effective treating more turbid rainy season NRG dugout water (931NTU) (Foran, 2007).

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16.0 Appendices

Appendix A: Reductions of Bacteria, Viruses, and Protozoa by Treatment Processes

Table 23 Reductions of Bacteria, Viruses and Protozoa Achieved by Typical and Enhanced Water Treatment Processes (WHO, 2006 Microbial p. 26)

Treatment process	**Enteric pathogen group**	**Baseline removal**	**Maximum removal possible**
Pretreatment by roughing filters	Bacteria	50%	Up to 95% if protected from turbidity spikes by dynamic filter or if used only when ripened
	Viruses	No data available	
	Protozoa	No data available, some removal likely	Performance for protozoan removal likely to correspond to turbidity removal
Slow sand filtration	Bacteria	50%	99.5% under optimum ripening, cleaning and refilling and in the absence of short circuiting
	Viruses	20%	99.99% under optimum ripening, cleaning and refilling and in the absence of short circuiting
	Protozoa	50%	99% under optimum ripening, cleaning and refilling and in the absence of short circuiting
Disinfection Chlorine	Bacteria	Ct_{99}: 0.08 mg*min/liter at 1-2°C, pH 7; 3.3 mg*min/liter at 1-2°C, pH 8.5	

	Viruses	Ct_{99}: 12 mg*min/liter at 0-5°C; 8 mg*min/liter at 10°C; both at pH 7-7.5	
	Protozoa	*Giardia* Ct_{99}: 230 mg*min/liter at 0.5 °C; 100 mg*min/liter at 10°C; 41 mg*min/liter at 25°C; all at pH 7-7.5 *Cryptosporidium* not killed	

Appendix B: Pond Characteristics (Ludwig, 2005)

Pond Characteristics			
	Storage Ponds	**Living Ponds**	**Runoff Harvesting Ponds**
Characteristics	Open, earth-supported tanks	May look just like natural ponds	Seasonal pools of runoff - essentially big rain puddles
Lining	Usually EPDM rubber, sometimes concrete	Imported of native clay soil, or a liner covered with sand or gravel	Native soil
Plants and animals	Almost devoid of life, maybe a few mosquito fish and visiting birds	All the complexity of natural ponds, with an intricate web of plant, animal, and insect associations	Whatever can grow or live with alternating wet and dry conditions
Level fluctuation	Full to zero	Generally less than two feets	Full to zero
Depth	Deeper = less loss to evaporation	Deep enough to make cool refuge for fish, not so deep the bottom is oxygen-starved	Flexible, but generally shallow
Management & maintenance	Minimal - like a tank	High-to maintain ecological balance; weeding, stocking with fish, etc.	Minimal – monitor during big rain events

Water quality	Nearly drinkable	Low, often turbid and full of free-floating algae	Low, often turbid, and full of free-floating algae, tannins
Water source	Filled from an external source. Runoff is generally excluded	Filled from external source and/or underlying springs. Runoff may be captured, excluded, or be divertable	Filled entirely with captured runoff
Cost	High	High	Low

Uses			
Water storage	Whole volume	Top two feet only	Whole volume - if any
Groundwateter recharge	No	Maybe	Yes
Fishing	Maybe	Yes	Maybe, if full long enough
Swimming	Yes, but asethetics are often lacking	Yes, but pier or dive may be desirable to avoid mucky bottom	Seasonally, but often shallow and mucky
Wildlife benefit	Minimal	Considerable	Considerable
Aquaculture	Maybe	Yes	If full long enough. Can plant land crops as water recedes.
Typical accessories	Chain link fence	Pier diving platform	Laundry washboard.

Appendix C: Flow Rate Conversion Table

Table 24 Flow Rate Conversion Table from m/h to ml/min

m/hr	L/hr	ml/min
0.1	0.81	14
0.2	1.62	27
0.3	2.43	41
0.4	3.24	54
0.5	4.05	68
0.6	4.86	81
0.7	5.67	95
0.8	6.48	108
0.9	7.29	122

1.0	8.10	135
1.1	8.91	149
1.2	9.72	162
1.3	10.53	176
1.4	11.34	189
1.5	12.15	203
1.6	12.97	216
1.7	13.78	230
1.8	14.59	243
1.9	15.40	257
2.0	16.21	270
2.1	17.02	284
2.2	17.83	297
2.3	18.64	311
2.4	19.45	324
2.5	20.26	338
2.6	21.07	351
2.7	21.88	365
2.8	22.69	378
2.9	23.50	392
3.0	24.31	405

Appendix D: Relationship between Nephelometric Turbidity Units (NTU) and Turbidity Units (TU)

Table 25 NTU and TU t-Test

t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	151.1608	116.0392
Variance	7231.547	8858.878
Observations	51	51
Hypothesized Mean Difference	0	
df	99	
t Stat	1.977312	
P(T<=t) one-tail	0.025394	
t Critical one-tail	1.660391	
P(T<=t) two-tail	0.050787	
t Critical two-tail	1.984217	

For a t-Test, 5% probability or larger provides enough evidence that the differences between the two sets of data could have occurred through random chance. In Table 25, we see that the difference between the two techniques is significant in this case (2.5% < 5%). The p-value 0.03 is < 0.05 so the null hypothesis (that the NTU and TU do not differ) is rejected for the alternative, which is that NTU and TU do differ. Therefore, it is likely that there is significant difference between the outcomes of the NTU and TU tests.

Results from Ghanasco Dam field samples were tested with the turbidity tube in TU and the turbidimeter in NTU and compared. In addition, in the lab at MIT, clay was mixed with water to make turbid water. Turbidity measurements of this water were taken with the turbidity tube and turbidimeter (Table 26). A linear relationship was fit to both field and laboratory data separately (Figure 91) and together (Figure 92). The correlation between TU and NTU was found to be:

Equation 3 $$TU = 0.7408 * NTU$$

The turbidity tube results are highly dependent on the interpretation of the person taking the reading and the ambient light conditions.

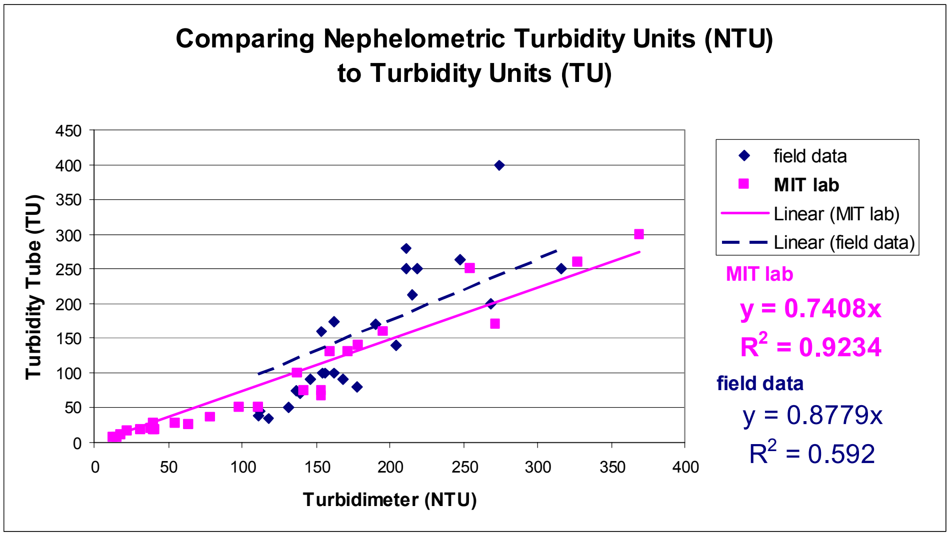


Figure 91 Comparison of NTU units and TU units

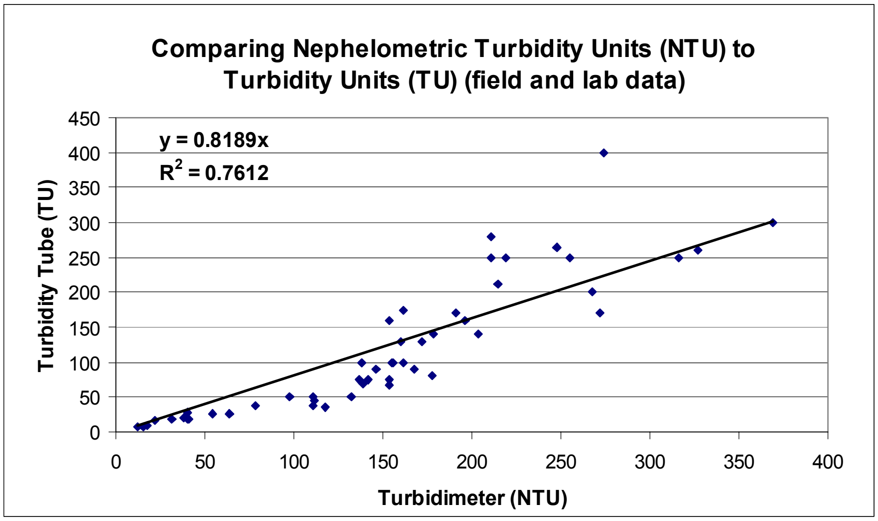


Figure 92 Comparison of NTU units and TU units – field and lab data

Table 26 TU and NTU Data from Ghana and MIT Lab

Date	Time	Description	turbidimeter (NTU)	Turbidity tube (TU)
		Ghanasco		
1/16/08	5:10 PM	G tank	211	250
1/16/08	5:10 PM	P tank	211	280
1/18/07	1:53 PM	G tank	154	159
1/18/07	1:53 PM	G tank	215	212
1/18/07	1:53 PM	P tank	162	175
1/18/07	1:53 PM	P tank	248	264
1/18/07	1:53 PM	G tank	156	100
1/18/07	1:53 PM	G tank	219	250
1/18/07	1:53 PM	P tank	146	90
1/18/07	1:53 PM	P tank	268	200
1/19/08	9:25 AM	G	118	35
1/19/08	9:25 AM	D	111	38
1/19/08	9:25 AM	P	137	75
1/19/08	9:48 AM	G tank	168	90
1/19/08	9:48 AM	G tank	274	400
1/19/08	10:07 AM	P tank	178	80
1/19/08	10:07 AM	P tank	316	250
1/19/08	12:15 PM	G*	112	45
1/19/08	12:15 PM	D*	132	50
1/19/08	12:15 PM	P*	139	70
1/24/08		G tank	155	100
1/24/08		G tank	191	170
1/24/08		P tank	162	100
1/24/08		P tank	204	140
MIT LAB				
4/11/08	5 g of Ghanasco dirt + 1 L water		255	250
4/11/08	5 g of Ghanasco dirt + 1 L water		369	300
4/11/08	5 g of Ghanasco dirt + 1 L water		327	260
4/11/08	decanted		160	130
4/11/08	decanted		172	130
4/11/08	decanted		179	140
4/11/08	decanted		138	100
4/11/08	decanted		138	100
4/11/08	decanted		142	75
5/10/08	.3 g red clay +1 L of water		154	75
5/10/08	mixed		154	68
5/10/08	mixed		40.5	28

5/10/08	mixed		111	50
5/10/08	mixed		54.6	27
5/10/08	mixed		38.6	20
5/10/08	mixed		17.9	10
5/10/08	mixed		12.5	8
5/10/08	mixed		78.5	37
5/10/08	mixed		64.3	26
5/10/08	mixed		31.5	19
5/10/08	mixed		22	16
5/10/08	mixed		15.8	8
5/10/08	mixed		272	170
5/10/08	mixed		196	160
5/10/08	mixed		97.9	50
5/10/08	mixed		40.1	19
5/10/08	mixed		41	19

Appendix E: Pilot HRF Turbidity Test Results

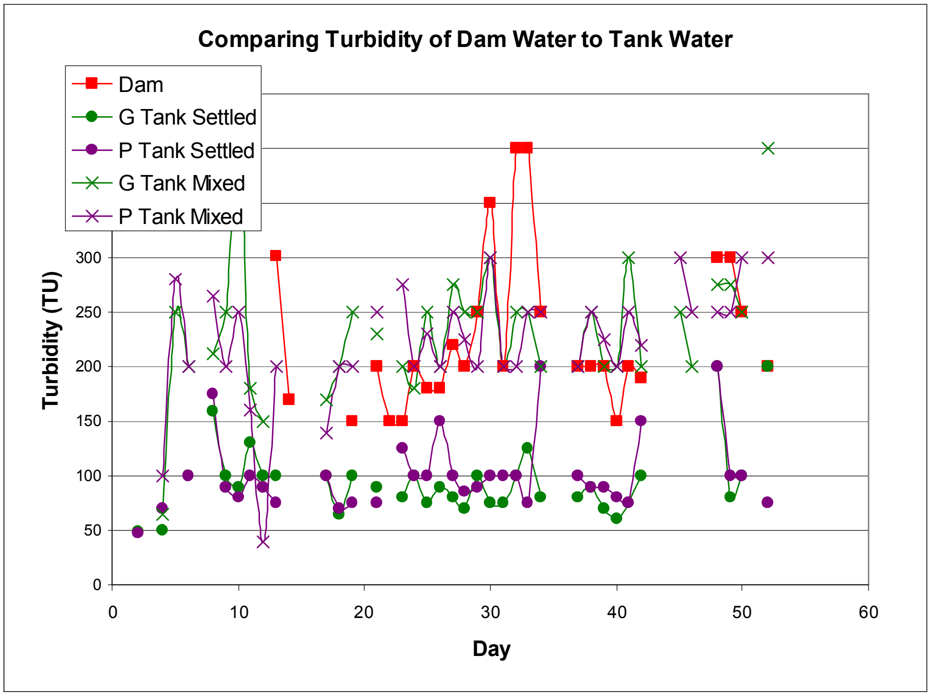
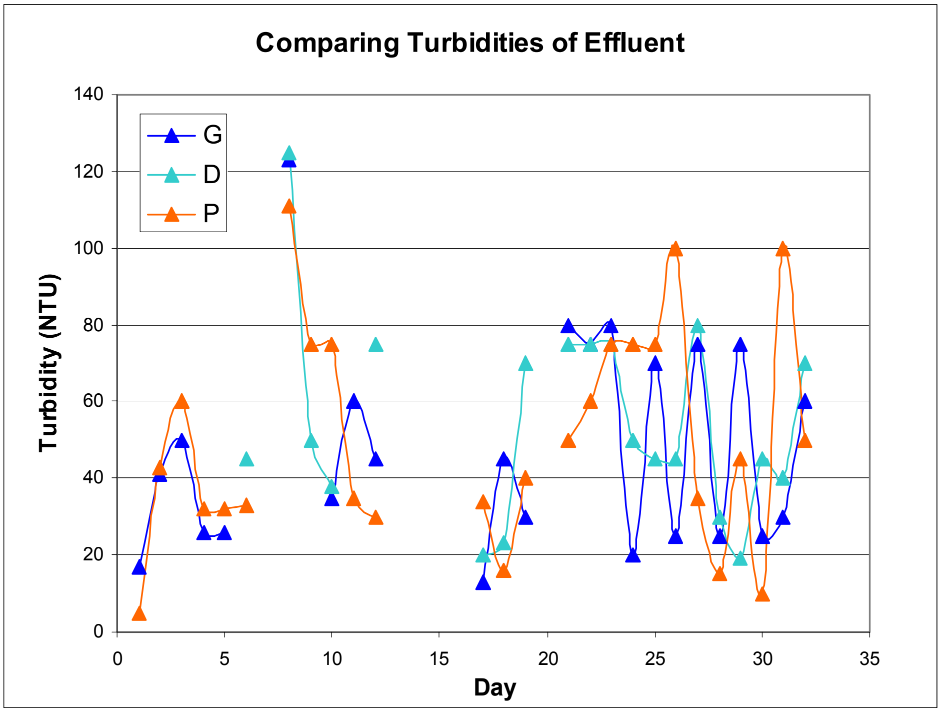


Figure 93 Comparing the Ghanasco Dam and tank turbidities



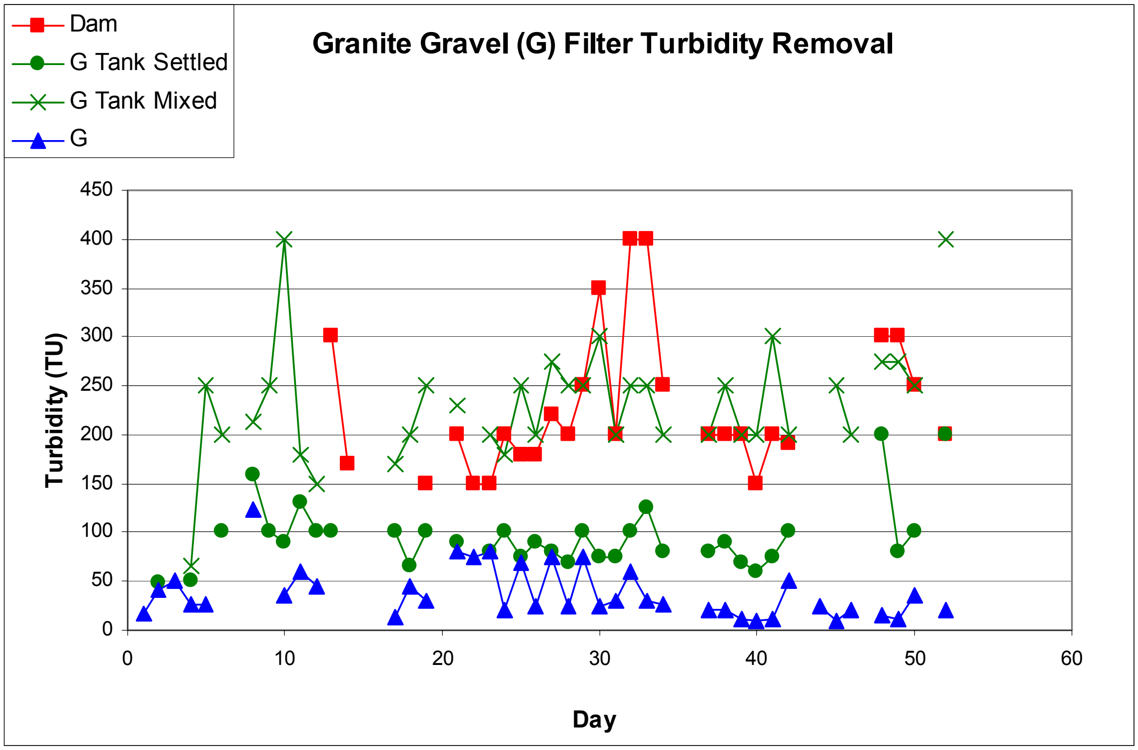


Figure 94 Granite gravel (G) turbidity removal

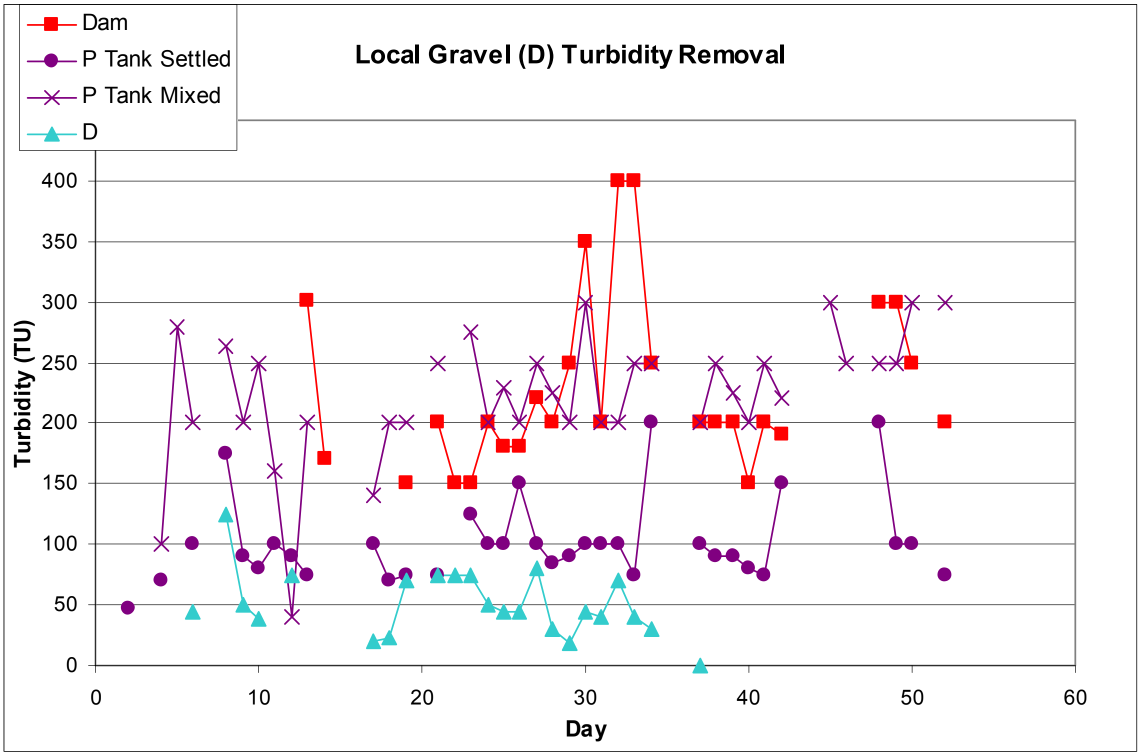


Figure 95 Local gravel (D) turbidity removal

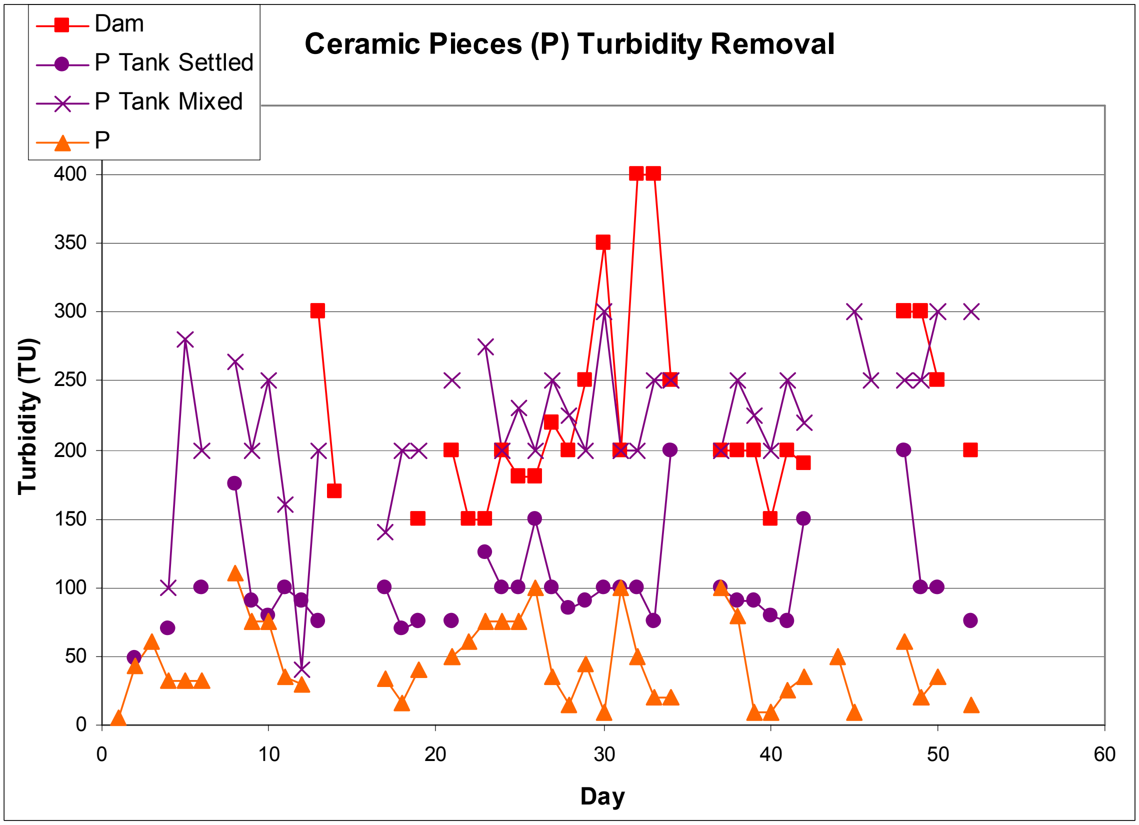


Figure 96 Broken pottery (P) turbidity removal

Appendix F: Dam Physical Water Test Data

Table 27 Ghanasco Dam Physical Water Test Results

Date			17-Jan	17-Jan
Time			12:00 PM	12:00 PM
Description		Ghanasco	Ghanasco	Ghanasco
Notes		New dugout water	different	
Turbidity (NTU)		211	202	177
Filtrability (mL)	1 min		65	
	2 min		80	
	3 min		88	
Suspension stability (NTU)	0 min	0		
	15 min	15		
	20 min	20		
	60 min	60		
	90 min	90		
	120 min	120		
	4 hr	240		
	8 hr	480		
	24 hr	1440		
	32 hr	1920		
	50 hr	3000		
Sequential filtration (NTU)	initial		192.0	
	1 um		78.8	
	8 - 12 um		148	
	20 - 30 um		164	
Solids settleability (mL)	15 min			
	30 min			
	1 hr			
	2 hr			
	4 hr			
	8 hr			
	24 hr			

Table 28 Kpanvo Dam, Gbrumani Dam, and Kunyevilla Dam Physical Water Test Results

Date		17-Jan	17-Jan	17-Jan	21-Jan	21-Jan	21-Jan
Time		10:30 AM	10:30 AM	10:30 AM	12:25 PM	12:25 PM	12:25 PM
Description		Kpanvo	Kpanvo	Kpanvo	Gbrumani	Gbrumani	Kunyevilla
Notes		Soka pump and cloth filter	Soka pump and cloth filter		Dugout	Tap	Dugout
Turbidity (NTU)		109	107	116	48.2	27.8	124
Filtrability (NTU)		85			87	110	55
		120			125	175	60
		140			150	210	70
Suspension stability (NTU)	0 min	107	87.4	113	48.2	27.8	124
	15 min	55.9	62.8		39.5	22.1	101
	20 min	54.6	73.8		40.3	23	94.6
	60 min			89.8	37.2	23	77.5
	90 min	62.3	49.2	91.2	34.4	21.5	78.4
	120 min	55.4	47.2	59.3	28.4	21.9	35.3
	330 min	45.8	36.5	59.5	30	21.7	46.5
	420 min	31.2	33.5	39.2			
	1530 min	28.9	31.3	28.5	11.6	20.9	19.5
	2880 min	23.9	24.6	27.3	7.94	17.2	9.82
Sequential filtration (NTU)				115.0	48.2	27.8	124.0
				145	11.2	6.04	3.28
				65.1	29.2	10.5	18.8
				80.3	38.6	16.9	53.7
Solids settleability (mL)			<1				1
			<1				1
			<1				1
			<1				1
			<1				2
			<1				2
			<1				2

Appendix G: Ghanasco Dam Pilot HRF Monitoring Data

Table 29 Pilot HRF Monitoring Data (1)

Date	Time	Initial Flow Rate (mL/min)			Tube Turibidity (TU)			Tank Levels (cm)		Tank Turbidity (TU)			
		G	D	P	G	D	P	G	P	G no mix	G mix	P no mix	P mix
1-13	10:00				17		5	90	88				
1-14	10:00				41		43	85	65	49		48	
1-14	14:30	650		160	50		60	75	58				
1-15	9:30	0		150	26		32	70	32	50	65	70	100
1-16	17:10	38	110	40	26		32	35	44		250		280
1-17	10:50	21	48	5		45	33	33	40	100	200	100	200
1-17	15:00	60	178	165									
1-18	14:08	0	135	5	123	125	111	32	20	159	212	175	264
1-18	16:34	5	85	152		50	75	30	10	100	250	90	200
1-19	9:18	31	80	96	35	38	75	12	15	90	400	80	250
1-19	16:30	161	0	30	60		35	30	32	130	180	100	160
1-20	15:20	3	5	0	45	75	30	35	40	100	150	90	40
1-20	17:24	0	38	80				32	27	100		75	200
1-21													
1-22		0	5	20				32	18				
1-23	15:20	3	3	5				40	44				
1-24	10:20	0	0	0	13	20	34	35	37	100	170	100	140
1-25	15:20	3	0	17	45	23	16	31	31	65	200	70	200
1-26	13:00	13	0	159	30	70	40	3	7	100	250	75	200
1-27													
1-28	16:00	0	0	0	80	75	50	36	39	90	230	75	250
1-29	13:00	0	0	0	75	75	60	1	3				
1-30	14:00	0	0	0	80	75	75	24	36	80	200	125	275
1-31	9:00	0	0	0	20	50	75	34	37	100	180	100	200
2-1	8:00	0	18	16	70	45	75	29	37	75	250	100	230
2-2	16:00	0	15	0	25	45	100	37	35	90	200	150	200
2-3	15:30	0	0	0	75	80	35	33	33	80	275	100	250
2-4	13:00	0.75	34	1.9	25	30	15	32	33	70	250	85	225

2-5	15:00	0	75	46	75	19	45	31	41	100	250	90	200
2-6	16:30	0	55	10	25	45	10	28	23	75	300	100	300
2-7	16:00	0	49	0.5	30	40	100	32	26	75	200	100	200
2-8	16:30	114	180	0	60	70	50	27	29	100	250	100	200
2-9	17:00	47	87	0	30	40	20	28	17	125	250	75	250
2-10	7:30	0	222	30	27	30	20	32	27	80	200	200	250
2-11													
2-12													
2-13	16:00	0		0	20	** **	100	32	28	80	200	100	200
2-14	15:00	0		0	20		80	30	32	90	250	90	250
2-15	14:00	0		0	12		10	37	35	70	200	90	225
2-16	16:00	0		3	10		10	34	40	60	200	80	200
2-17	16:00	0		27	12		25	35	32	75	300	75	250
2-18	16:00	0		32	50		35	31	35	100	200	150	220
2-19													
2-20	10:00	0		7	25		50	33	20				
2-21	13:40	0		0	10		10	32	28		250		300
2-22	13:00	0		0	20			26	25		200		250
2-23													
2-24	14:00	0		0	15		60	30	29	200	275	200	250
2-25	16:00	0		40	12		20	22	32	80	275	100	250
2-26	17:00	0		35	35		35	34	32	100	250	100	300
2-27													
2-28	17:00	0		0	20		15	7	24	200	400	75	300
	*** D-tube valve broke												

Table 30 Pilot HRF Monitoring Data Continued (2)

Date	**Time**	**Final Flow Rate (mL/min)**			**Dam Turbidity (TU)**	**Day #**
		G	D	P	Dam	
1/13	10:00					1
1/14	10:00					2
1/14	14:30	250		250		3
1/15	9:30	120		150		4
1/16	17:10	38	110	40		5
1/17	10:50					6
1/17	15:00					7
1/18	14:08	300	135	21		8
1/18	16:34	270	184	152		9
1/19	9:18	64	115	90		10

1/19	16:30	161	3	17		11
1/20	15:20	8	65	17		12
1/20	17:24	140	38	80	301 NTU	13
1/21					176 NTU	14
1/22		217	278	255		15
1/23	15:20		100			16
1/24	10:20	32	126	27.5		17
1/25	15:20	512	400	173		18
1/26	13:00	164	475	73	150	19
1/27						20
1/28	16:00	424	174	116	200	21
1/29	13:00	117	60	477	150	22
1/30	14:00	100	182	564	150	23
1/31	9:00	110	431	407	200	24
2/1	8:00	102	631	644	180	25
2/2	16:00	126	525	208	180	26
2/3	15:30	420	221	85	220	27
2/4	13:00	267	218	405	200	28
2/5	15:00	131	200	380	250	29
2/6	16:30	320	540	520	350	30
2/7	16:00	454	290	385	200	31
2/8	16:30	114	180	452	400	32
2/9	17:00	170	360	427	400	33
2/10	7:30	523	360	535	250	34
2/11						35
2/12						36
2/13	16:00	265		294	200	37
2/14	15:00	292		371	200	38
2/15	14:00	194		315	200	39
2/16	16:00	342		145	150	40
2/17	16:00	360		209	200	41
2/18	16:00	180		280	190	42
2/19						43
2/20	10:00	275		150		44
2/21	13:40	312		225		45
2/22	13:00	141		162		46
2/23						47
2/24	14:00	290		240	300	48
2/25	16:00	49		70	300	49
2/26	17:00	87		320	250	50
2/27						51
2/28	17:00	285		220	200	52

Appendix H: Ghanasco Dam Pilot HRF Physical Water Test Data

Table 31 Ghanasco Dam Pilot HRF Physical Water Test Data (1)

Date		1-16	1-16	1-18	1-18	1-18	1-18	1-18
Time		5:10 PM	5:10 PM	1:53 PM	1:53 PM	1:53 PM	1:53 PM	1:53 PM
Description		G tank	P tank	G	D	P	G tank	G tank
Notes			test 1/17		before stir		no mix	Mixed
Turbidity (NTU)				300	135	21		
Filtrability (NTU)	initial			123	125	111	154	215
	1 min				70	60	50	55
	2 min				80	75	60	60
	3 min				110	85	70	70
Suspension stability (NTU)	0 min		201					
	15 min	170	200					
	20 min	162	194					
	60 min	168	189					
	90 min	163	184					
	120 min	159	179					
	4 hr	146	170					
	8 hr							
	24 hr	128	137					
	32 hr	134	122					
	50 hr	125	115					
Sequential filtration (NTU)	0.0			121	124	116	154	215
	1 um			67.4	76.6	28.9	69	71.3
	8 - 12 um			109	110	93.2	113	125
	20 - 30 um			114	118	106	126	150

Table 32 Ghanasco Dam Pilot HRF Physical Water Test Data (2)

Date		1-18	1-18	1-18	1-18	1-18	1-18	1-18
Time		1:53 PM	1:53 PM	4:30 PM	4:30 PM	4:30 PM	1:53 PM	1:53 PM
Description		P tank	P tank	G	D	P	G tank	G tank
Notes		no mix	mixed			test 1/20	no mix	Mixed
Turbidity (NTU)				270	184	152		
Filtrability (NTU)	initial	162	248	82.1	125	116	156	219
	1 min	60	60	80	60	50	60	55
	2 min	70	65	110	80	60	75	60
	3 min	80	70	130	85	70	80	65
Sequential filtration (NTU)	0.0	162.0	248.0					
	1 um	91.5	102					
	8 - 12 um	125	121					
	20 - 30 um	151	174					

Table 33 Ghanasco Dam Pilot HRF Physical Water Test Data (3)

Date		1-18	1-18	1-19	1-19	1-19	1-19	1-19
Time		1:53 PM	1:53 PM	9:25 AM	9:25 AM	9:25 AM	9:48 AM	9:48 AM
Description		P tank	P tank	G	D	P	G tank	G tank
Notes		no mix	mixed				no mix	Mixed
Turbidity (NTU)				31	80	96		
Filtrability (NTU)	initial	146	268	118	111	137	168	274
	1 min	60	55					
	2 min	80	60					
	3 min	90	65					

Table 34 Ghanasco Dam Pilot HRF Physical Water Test Data (4)

Date		1-19	1-19	1-19	1-19	1-19	1-20	1-20
Time		10:07 AM	10:07 AM	12:15 PM	12:15 PM	12:15 PM	3:40 PM	3:40 PM
Description		P tank	P tank	G	D	P	G	D
Notes		no mix	mixed					
Turbidity (NTU)				64	115	90	140	38
Filtrability (NTU)	initial	178	316	112	132	139	122	167
	1 min						70	70
	2 min						100	80
	3 min						110	90
Sequential filtration (NTU)	0.0						122.0	167.0
	1 um						69.4	56.3
	8 - 12 um						106	72.3
	20 - 30 um						114	84

Table 35 Ghanasco Dam Pilot HRF Physical Water Test Data (5)

Date		1-20n	1-20	1-20	1-20	1-20	1-21	1-21
Time		3:40 PM	3:50 PM	3:50 PM	3:45 PM	3:45 PM	5:26 PM	5:26 PM
Description		P	G tank	G tank	P tank	P tank	G	D
Notes			no mix	mixed	no mix	Mixed		
Turbidity (NTU)		80						
Filtrability (NTU)	initial	109	168	231	178	239	93.2	111
	1 min	60	60	50	65	60	70	70
	2 min	70	70	58	80	65	100	105
	3 min	75	78	60	85	70	120	120
Sequential filtration (NTU)	0.0	109.0	168.0	231.0	178.0	239.0		
	1 um	49.4	66.5	77.3	84.5	88.1		
	8 - 12 um	95.7	137	137	142	144		
	20 - 30um	98.1	155		153	184		

Table 36 Ghanasco Dam Pilot HRF Physical Water Test Data (6)

Date		1-21			1-22	1-22	1-22
Time		5:26 PM			5:26 PM	5:26 PM	5:26 PM
Description		P			G tank	G tank	G
Notes					no mix	mixed	
Turbidity (NTU)							
Filtrability (NTU)	initial	96.3			145	216	63.8
	1 min	60			60	55	75
	2 min	75			80	65	115
	3 min	80			85	70	135
Suspension stability (NTU)	0 min		9:05 AM	0 min	145	216	63.8
	15 min		9:20 AM	15 min	140	174	57.2
	20 min		9:25 AM	20 min	140	175	58.6
	60 min		10:05AM	60 min	143	163	57.8
	90 min		10:35 AM	90 min			
	120 min		11:05 AM	120 min	140	154	57.8
	4 hr		1:05 PM	240 min	140	154	59.3
	8 hr		4:00 PM	420 min			
	24 hr		9:05 AM	1440 min	125	128	56.9
	32 hr		2:00 PM	1740 min	120	126	54.9
	50 hr		-----				
Sequential filtration (NTU)	0.0				145.0	216.0	63.8
	1 um				64.8	73.5	33.8
	8 - 12 um				118	132	51.1
	20 - 30 um				130	172	54.4

Table 37 Ghanasco Dam Pilot HRF Physical Water Test Data (7)

Date		1-22	1-22	1-23	1-23	1-23	1-23	1-23
Time		5:26 PM	5:26 PM	3:30 PM	3:30 PM	3:30 PM	3:30 PM	3:30 PM
Description		D	P	G tank	G tank	P tank	P tank	G
Notes				no mix	Mixed	no mix	mixed	
Turbidity (NTU)								3
Filtrability (NTU)	initial	84	101	160	188	155	198	71.3
	1 min	130	65	60	65	70	60	
	2 min	135	80	80	70	85	70	
	3 min	140	95	85	80	90	80	
Suspension stability (NTU)	0 min	84	101					
	15 min	81.9	99.9					
	20 min	81.7	98.6					
	60 min	80.5	98.2					
	90 min							
	120 min	81	97.8					
	4 hr	80	101					
	8 hr							
	24 hr	76.7	92.6					
	32 hr	76.6	89.6					
	50 hr							
Sequential filtration (NTU)	0.0	84.0	101.0					
	1 um	50.2	43.5					
	8 - 12 um	73.8	81.9					
	20 - 30 um	71.7	94.7					

Table 38 Ghanasco Dam Pilot HRF Physical Water Test Data (9)

Date		1-23	1-23	1-23	1-23			1-24
Time		3:30 PM	3:30 PM	3:30 PM	3:30 PM			
Description		D	D	P	dust test			G tank
Notes								no mix
Turbidity (NTU)		3	100	5				
Filtrability (NTU)	initial	129	101	54.9	140			155
	1 min							70
	2 min							85
	3 min							90
Suspension stability (NTU)	0 min					2:05 PM	0 min	155
	15 min					2:20 PM	15 min	149
	20 min					2:25 PM	20 min	152
	60 min					3:05 PM	60 min	148
	90 min					3:30 PM	85 min	148
	120 min					4:05 PM	120 min	149
	4 hr					6:05 PM	240 min	146
	8 hr					2:05 PM	1440 min	136
	24 hr							
	32 hr							
	50 hr							
Sequential filtration (NTU)	0.0							155
	1 um							83.3
	8 - 12 um							131.0
	20 - 30 um							140

Table 39 Ghanasco Dam Pilot HRF Physical Water Test Data (10)

Date		1-24	1-24	1-24	1-24	1-24	1-24
Time							
Description		G tank	P tank	P tank	G Granite Gravel	D Local Gravel	P Broken Pottery
Notes		mixed	no mix	mixed			
Turbidity (NTU)					32	126	27.5
Filtrability (NTU)	initial	191	162	204	47.5	83.2	114
	1 min	50	80	60	90	100	60
	2 min	53	110	70	140	138	90
	3 min	60	130	75	160	160	100
Suspension stability (NTU)	0 min	191	162	204	47.5	83.2	114
	15 min	183	155	193	46.3	78.2	112
	20 min	177	158	191	46.2	80.6	113
	60 min	174	154	184	46	80.6	108
	90 min	175	154	169	46.9	82.1	110
	120 min	170	151	171	46.8	80.3	110
	4 hr	161	145	166	47.7	79.7	109
	8 hr	133	137	135	44.4	77.4	102
	24 hr						
	32 hr						
	50 hr						
Sequential filtration (NTU)	0.0	191	162	204	47.5	83.2	114
	1 um	95.1	85.4	80.7	35.6	56.2	50.4
	8 - 12 um	144.0	139.0	141.0	48.2	71.9	100.0
	20 - 30 um	161	146	170	44	72.9	111

Appendix I: Microbial Results

Sampling date		16-Jan	16-Jan	23-Jan	23-Jan	27-Jan
Location		Ghanasco	Ghanasco	Ghanasco	Ghanasco	Ghanasco
Type		Inlet/Dam	Inlet/Dam	Inlet/Dam	Inlet/Dam	Inlet/Dam
Sample Name		Dugout	Dugout	Dugout	Dugout	Dugout
Dilution		10000	100000	1000	10000	100
E.Coli (red)	CFU/plate	0	0	5	1	95
Other (blue)	CFU/plate	0	0	0	0	1
E.Coli (red)	CFU/100 mL	0	0	5000	10000	9500
Other (blue)	CFU/100 mL	0	0	0	0	100
Test Peformed by		Dreyfuss	Dreyfuss	Dreyfuss	Dreyfuss	Dreyfuss

Sampling date		27-Jan	19-Jan	19-Jan	19-Jan	19-Jan
Location		Ghanasco	Ghanasco	Ghanasco	Ghanasco	Ghanasco
Type		Inlet/Dam	Inlet/Dam	Inlet/Dam	Inlet/Dam	Inlet/Dam
Sample Name		Dugout	Tank P	Tank P	Tank P	Tank P
Dilution		1000	10000	100,000	1000	1000
E.Coli (red)	CFU/plate	9	1	0	1	0
Other (blue)	CFU/plate	0	0	0	0	0
E.Coli (red)	CFU/100 mL	9000	10000	0	1000	0
Other (blue)	CFU/100 mL	0	0	0	0	0
Test Peformed by		Dreyfuss	Walewijk	Walewijk	Dreyfuss	Dreyfuss

Sampling date		19-Jan	19-Jan	19-Jan	19-Jan	19-Jan
Location		Ghanasco	Ghanasco	Ghanasco	Ghanasco	Ghanasco
Type		Roughing	Roughing	Roughing	Roughing	Roughing
Sample Name		D4	D4	D4	D4	P4
Dilution		1000	10000	1000	10000	1000
E.Coli (red)	CFU/plate	21	1	21	1	1

Other (blue)	**CFU/plate**	0	0	0	0	1
E.Coli (red)	**CFU/100 mL**	21000	10000	21000	10000	1000
Other (blue)	**CFU/100 mL**	0	0	0	0	1000
Test Peformed by		Walewijk	Walewijk	Dreyfuss	Dreyfuss	Walewijk

Sampling date		19-Jan	19-Jan	19-Jan	16-Jan	16-Jan
Location		Ghanasco	Ghanasco	Ghanasco	Kpanvo	Kpanvo
Type		Roughing	Roughing	Roughing	Inlet/Dam	Inlet/Dam
Sample Name		P4	P4	P4	Dugout	Dugout
Dilution		10000	1000	10000	10000	100000
E.Coli (red)	**CFU/plate**	0	1	0	1	21
Other (blue)	**CFU/plate**	0	1	0	0	4
E.Coli (red)	**CFU/100 mL**	0	1000	0	10000	2100000
Other (blue)	**CFU/100 mL**	0	1000	0	0	400000
Test Peformed by		Walewijk	Dreyfuss	Dreyfuss	Dreyfuss	Dreyfuss

Sampling date		17-Jan	17-Jan	21-Jan	21-Jan	27-Jan	27-Jan
Location		Kpanvo	Kpanvo	Kpanvo	Kpanvo	Kpanvo	Kpanvo
Type		Inlet/Dam	Inlet/Dam	Inlet/Dam	Inlet/Dam	Inlet/Dam	Inlet/Dam
Sample Name		Dugout	Dugout	Dugout	Dugout	Dugout	Dugout
Dilution		10000	100000	1000	10000	1000	10000
E.Coli (red)	**CFU/plate**	3	0	21	0	3	1
Other (blue)	**CFU/plate**	1	0	0	0	0	0
E.Coli (red)	**CFU/100 mL**	30000	0	21000	0	3000	10000
Other (blue)	**CFU/100 mL**	10000	0	0	0	0	0
Test Peformed by		Dreyfuss	Dreyfuss	Dreyfuss	Dreyfuss	Dreyfuss	Dreyfuss