Appropriate Technology Water Treatment Processes for MaeLa Temporary Shelter, Thailand

By

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Submitted to the Department of Civil and Environmental Engineering
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ABSTRACT

This thesis recommends the use of horizontal-flow roughing filters to treat spring water of variable annual quality in MaeLa Temporary Shelter, Thailand. The public drinking water system for 45,000 refugees is overseen by Aide Médicale Internacionale, with which this project was conducted. Half the drinking water for the camp is provided by thirteen springs. The volume and turbidity of these springs varies annually, correlating with the rainy and dry seasons.

Treating the varying turbidity and volume at these sources so that the water can be effectively disinfected is the treatment goal. Available materials and operation and maintenance capabilities are also design parameters. Horizontal-flow roughing filtration was determined to fit these parameters and a design with two equivalent filters operating in parallel is recommended. One important feature of the filters is baffles that dictate the flow path of water through the filter. A second feature is an outflow at the top of the filter that will maintain a constant water volume in the filter. The feasibility of the design is based on flow tests and turbidity measurements taken on site as well as weekly flow rates and turbidities for 2007 provided by AMI. The requirements for mechanical regeneration of the filter are also determined.

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To my mom and my sister, who have made me the person I am today.

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LIST OF ABBREVIATIONS

ºC – degrees Celsius
AMI – Aide Médicale Internacionale
CFU mL^{-1} – Colony Forming Units per milliliter
cm – centimeters
E. coli – Escherichia coli
g – grams
HFRF – horizontal-flow roughing filter
kg m^{-3} – kilograms per cubic meter
km – kilometers
KNLA – Karen National Liberation Army
m – meters
m hr^{-1} – meters per hour
m min^{-1} – meters per minute
m^3 – cubic meters
m^3 min^{-1} – cubic meters per minute
mg – milligrams
mg L^{-1} – milligrams per Liter
min – minutes
mL – milliliters
mm – millimeters
NGO – Non-governmental organization
NTU – Nephelometric Turbidity Unit
ppm – parts per million
RF – roughing filter
SP – spring drinking water source in MaeLa
SP-10 – Spring 10
SP-X – Spring X
TBBC – Thailand Burma Border Consortium
UN – United Nations
UNHCR – United Nations High Commissioner on Refugees
UNICEF – United Nations Children's Fund
USD – United States Dollar
US EPA – United States Environmental Protection Agency
VFRF – vertical-flow roughing filter
WHO – World Health Organization

1 INTRODUCTION

Among the 1.1 billion people worldwide without UN-qualified improved drinking water, refugees are a population with unique needs (UNICEF & WHO, 2004). According to the 1951 Geneva Refugee Convention a refugee is defined as,

> "A person who, owning to a well-founded fear of being persecuted for reasons of race, religion, nationality, membership of a particular social group or political opinion, is outside the country of his nationality and is unable or, owning to such fear, is unwilling to avail himself of the protection of that country" (UNHCR, 2003).

Upon fleeing, refugees find themselves reliant on local governments and NGOs to provide assistance with basic human needs. For over twenty years, Karen people have been fleeing Myanmar (Burma) to Thailand to escape persecution from the military junta which is in power. There are two million refugees living legally and illegally in Thailand along the Myanmar (Burma) border, including 50,000 in MaeLa Temporary Shelter (TBBC, No Date; UNHCR, 2007).

MaeLa has existed for over twenty years and has an improved water system. The water is drawn from a nearby river and from springs, is chlorinated in most cases, and released into a pipe-tap network. Seasonal variation in rainfall results in variable water quality from both sources. The purpose of this thesis is to evaluate and propose modifications to an existing roughing filter, which is in use at one of the springs. In addition, the design of a flow-scalable roughing filter is discussed for potential use at the other springs. The successful implementation and maintenance of filters can help maintain spring-water quality at an annual average, dampening the impacts of seasonal rain variation.

The Thailand-Myanmar (Burma) border climate, economics, and history are further discussed in Chapter 2. Chapter 3 outlines the water system in MaeLa, including the locations of the various sources and some information on seasonal water quality variation. Chapters 2 and 3 were the result of a collaboration of the author, Mary Harding, and Navid Rahimi. Roughing filter technology is detailed in Chapter 4, including its ability to reduce influent water turbidity and microbial contamination. Chapters 5 and 6 explain the field work conducted on-site and the results of that work. Based on this information, modifications to the existing filter are recommended and the design of new filters is addressed in Chapter 7.

2 THE THAILAND – MYANMAR (BURMA) BORDER

Today there are nine UN refugee camps along the Thai-Myanmar (Burma) border where about 140,000 official refugees of the Karen and Karenni ethnic minorities have sought refuge from political persecution by the leadership of Myanmar (Burma) (CIA World Factbook, 2008; UNHCR, 2006). People living in the camps have traveled long distances to escape harm and face further battles adjusting to life in camp and making repatriation decisions. Understanding the political and economic situation of the people as well as the climate of the area frames the problem of providing safe drinking water.

2.1 Politics

In September 1988, a military junta took control in Myanmar (Burma) (Lanser, 2006). The military regime placed restrictions on work and civil liberties and became increasingly brutal, especially towards ethnic minorities. As a result, a large number of citizens fled from Myanmar (Burma) to escape persecution and to seek work. It is estimated that the largest number migrated into Thailand; although the exact numbers are unknown (TBBC, 2007). Of these, about 140,000 reside in UN-sanctioned camps and another 500,000 are registered migrant workers. The rest remain unregistered and attempt to live unnoticed in Thailand in order to avoid deportation (Fogarty, 2007).

Much of the challenge for these migrants stems from the fact that Thailand is not a signatory of the UN Refugee Convention. As such, the government only grants asylum to those fleeing combat as opposed to those fleeing human rights violations (Refugees International, 2007). The UN-sanctioned camps along the border, as a result, are not recognized by the Thai government as refugee camps. They are instead called temporary shelters, even though they have existed for more than twenty years. The Thai government expects on paper that the refugees to promptly return to Myanmar (Burma) or repatriate to another nation, but fortunately has allowed these camps to exist for decades.

Native hill tribes, which historically lived across an area covering parts of northern Thailand and Myanmar (Burma), make up a large majority of those seeking asylum. The Karen, Karenni, and Mon are the main tribes being driven from their homes by the Myanmar (Burma) military (McGeown, 2007). Within Myanmar (Burma) there is some resistance from the Karen National Liberation Army (KNLA) which is fighting for an independent Karen state. There are additional rebel armies, but over the past 20 years most have agreed to ceasefires with the military junta. Many of the refugees in the camps in Thailand are sympathetic to the KNLA, and some have even served in it (McGeown, 2007).

2.2 Economy

There is a significant amount of poverty in Myanmar (Burma) as a result of the military junta's controls and inefficient economic policies. Inconsistent exchange rates and a large national deficit create an overall unstable financial atmosphere (CBS, 2007). Although difficult to accurately assess, it is estimated that the black market and border trade could encompass as much as half of Myanmar's (Burma's) economy. Importing many basic commodities is banned by the Myanmar (Burma) government and exportation requires time and money (McGeown, 2007). Timber, drugs, gemstones and rice are major imports into Thailand, while fuel and basic consumer goods such as textiles and furniture are returned (CBS, 2007).

By night, the Moei River, which divides the two countries, is bustling with illicit activity. Through bribing several officials, those who ford the river are able to earn a modest profit (for example, around two USD for a load of furniture) and provide a service to area merchants and communities. Thailand benefits from a robust gemstone business that draws dealers from all over the world. The Myanmar (Burma) mine owners would get a fraction of the profit by dealing directly with the Myanmar government, so instead choose to sell on the black market (McGeown, 2007).

The Thai economy along the border also feels the impact of migrant workers. Many Thai business owners rely on illegal workers for cheap labor. In Mae Sot, the closest city to the MaeLa camp, it is estimated that only 50% of the 80,000 Myanmar (Burmese) people in the area have Thai work permits (McGeown, 2007). In addition to illegal business negotiations there are government bribes. Illegal residents often pay Thai authorities bribes in order to remain in Thailand. In other cases, migrants are deported only to return the same day after bribing Myanmar (Burmese) and Thai border officials. If illegal immigrants are reported to the Myanmar (Burma) government, however, heftier fines must be paid in order to avoid jail time (McGeown, 2007).

2.3 Climate in Northwestern Thailand

The Tak region of northwestern Thailand is characterized by a tropical climate with wet and dry seasons (UN Thailand, 2006; ESS, 2002). The rainy season lasts from June to October, followed by a cool season until February. The weather turns hot and sunny between March and May (UN Thailand, 2006). This region of Thailand has an average temperature of 26ºC although there is significant variation during the year and, due to changes in elevation, over the region. Temperatures can range from 4ºC to 42ºC (Thailand Meteorological Department in ESS, 2002). The average annual rainfall in Mae Sot, Thailand is 2100 mm (GOSIC, 2007). Figure 2-1 shows the monthly rainfall averages over the past 56 years. During the wet season there is a clear increase in precipitation, as more than 85% of the annual rainfall occurs during this period.

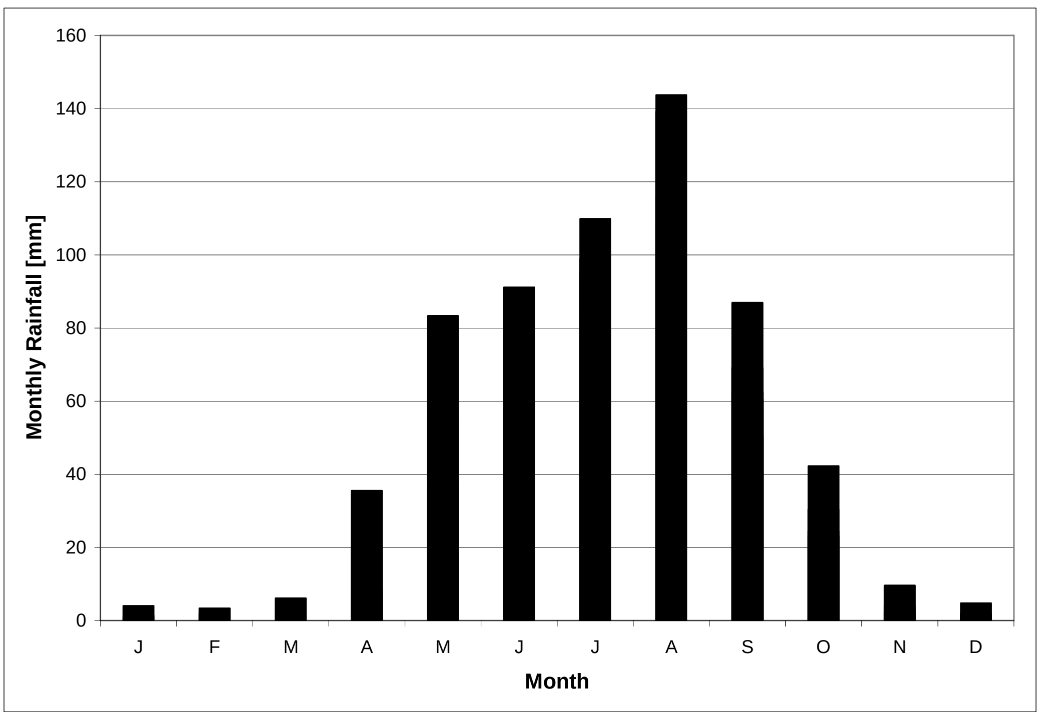


Figure 2-1: Average Monthly Rainfall for Mae Sot, Thailand (GOSIC, 2007).

2.4 MaeLa Camp

The MaeLa camp is a refuge for people seeking protection from the Myanmar (Burma) government and from warfare along the Thailand-Myanmar (Burma) border (McGeown, 2007). The camp is run by the United Nations High Commissioner on Refugees and has existed since 1984 (TBBC, No Date). MaeLa is located near 16º30'N and 98º30'E in the northern region of Thailand about ten kilometers from the border with Myanmar (Burma) (Lumjuan, 1982; TBBC, No Date). The camp location is shown by the red circle in Figure 2-2. The nearest town, Mae Sot, is about 60 kilometers away from MaeLa. The next nearest large city is Tak and Bangkok is about 500 kilometers south-east of Mae Sot (Google, 2007).

Figure 2-2: Location of the MaeLa Refugee Camp
(Map of the Mekong River Subregion, 2006).

2.4.1 Population Demographics

MaeLa is home to about 45,000 refugees, mainly of the Karen ethnic minority (UNHCR, 2007; TBBC, No Date). There are reportedly more than six million Karen people living in Myanmar (Burma) and about 400,000 living in Thailand (KarenPeople, 2004). These numbers may not account for the approximately 150,000 Karen refugees living in refugee camps in Thailand (UNHCR, 2007).

Figure 2-3 shows the relative populations, ethnicities, and age demographics of the UN refugee camps in Thailand. MaeLa is by far the largest camp, with a population of more than double the next largest. Interestingly all the camps have a similar age distribution of refugees, with about half the population between 18 and 59 years old and one-third between 5 and 17 years old.

The Karen believe strongly in the value of family. As a result, repatriation decisions are difficult and must be made as a family. Generally, the teenagers and young adults who have lived most or all of their lives inside the camp want to repatriate elsewhere while older generations hope to return to Burma if it is restored (D. Lantagne, personal communication, October 19, 2007).

The Karen are friendly, caring, and accepting. Children throughout the camp often receive a pat on the head from passers by and market areas within the camp are a bustle with conversations and negotiations. Within the bounds of the camp are a Muslim mosque, Buddhist monastery, and Christian churches, which refugees attend without fear of persecution.

While people within the camp are protected and provided with many provisions, they are still a transient population with disturbing pasts and uncertain futures. One refugee fled Myanmar (Burma) on foot with only the clothes on his back and some food for the journey in a shoulder bag. It took him over a month to reach the camp, traveling only at night and sometimes waiting days to be sure Myanmar (Burmese) authorities were not in the area. Once people arrive in the camp and decide to apply for repatriation, they can wait months to years to receive a decision.

2.4.2 Environment

The MaeLa camp is located in a valley surrounded by two ridges rising about 300 meters above the camp. These hills are distant extremities of the Himalayan mountain range which is mainly located northwest of Thailand. A river runs through the end of the two ridges and bounds the camp on the north. The Thai military protects the road that borders the camp and links it with the nearest Thai city of Mae Sot. These key boundaries are shown in Figure 2-4, where the camp is roughly circled in white. Figure 2-4 also shows some water infrastructure including several storage tanks and some spring locations.

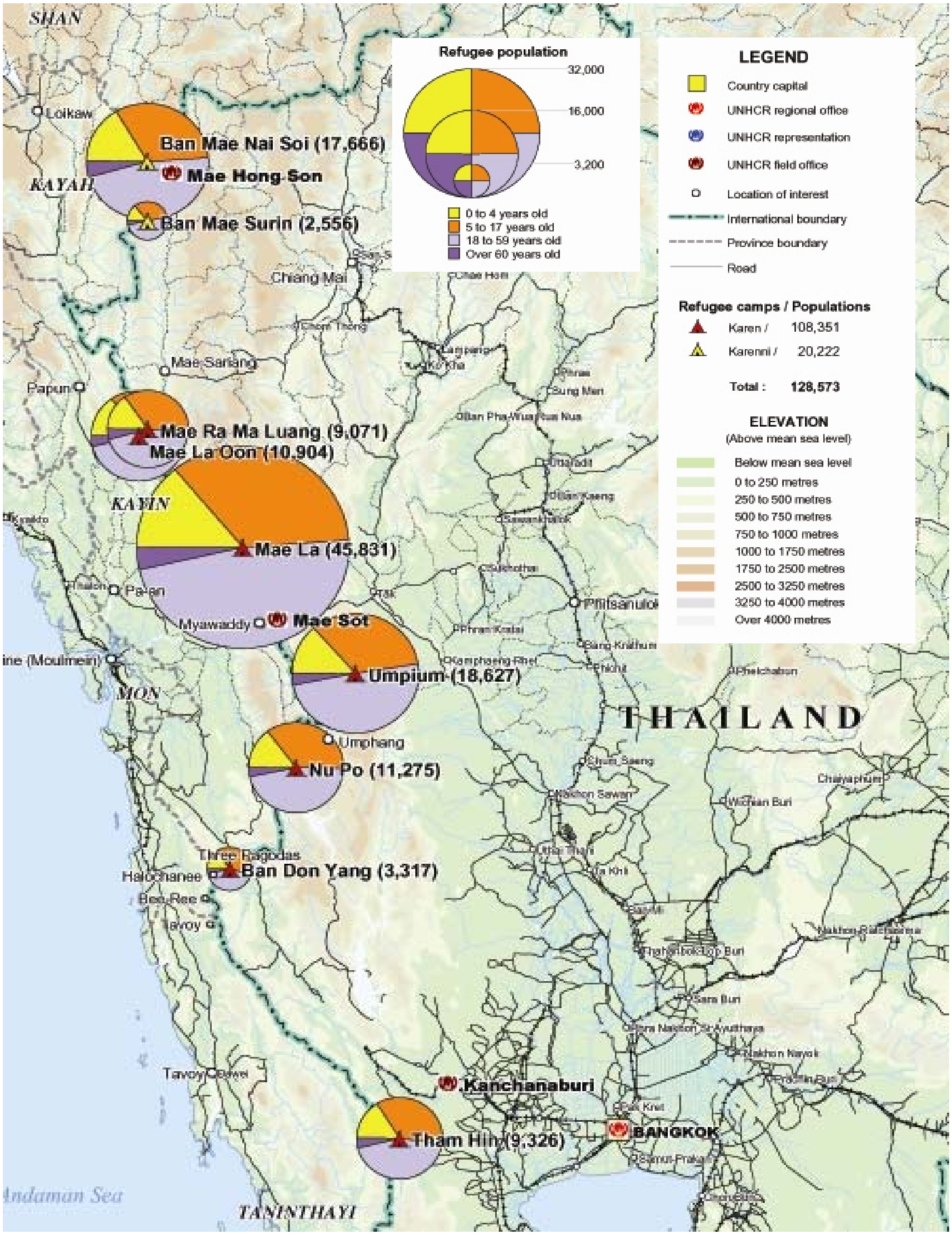


Figure 2-3: UN Refugee Camp Populations and Demographics (UNHCR, 2006).

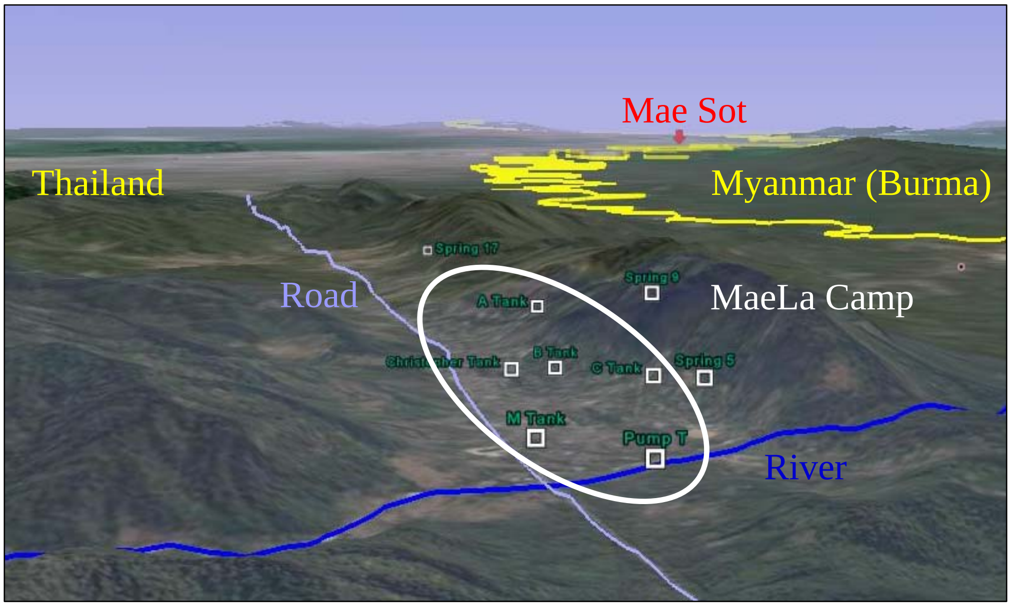


Figure 2-4: MaeLa Location, looking southwest
(Google Earth, 2007; Lantagne, 2007).

As a result of the Thai classification of the camp as a temporary shelter, the camp residents cannot cut down trees within the camp and must construct their buildings of non-permanent materials. The UN and other NGOs provide materials such as bamboo for building construction.

2.4.3 Public Health and Water Supply

There are about eleven NGOs that provide services within the camp ranging from food and shelter provisions, health care, protection, and water supply. Aide Médicale Internacionale (AMI) is currently charged with providing health care and water supply. In the fall of 2008, Solidarities, which already provides sanitation in the camp, will take over the water supply services. AMI has an international staff based in Mae Sot and provides services at MaeLa as well as at several other UN refugee camps.

The AMI MaeLa Water and Logistics Coordinator oversees a staff of about 30 refugees who operate the water system on a daily basis. The water system consists of drinking water supplied to public tap stands from surface and groundwater sources. In addition, non-potable water is provided throughout the camp by rope-pump and bore-hole groundwater supplies. The drinking water system is discussed in detail in Chapter 3.

3 DRINKING WATER IN MAELA

AMI maintains potable and non-potable public water supplies within MaeLa. This chapter outlines the sources of drinking water for the camp, the water system components, and existing treatment processes.

3.1 Drinking Water Sources

The drinking water sources in MaeLa are surface water from the river and naturally flowing springs. The river runs east-west, cross-cutting through the north end of the southwest facing ridge that borders the camp. While the river is an important water supply for the camp, its existing quality and potential means of treatment are not the focus of this work. The thirteen springs that are used for public drinking water supply flow from the ridge that borders the camp to the southwest and their quality is the focus of this thesis.

There is annual variability in the volume of drinking water available in total and from each source. Figure 3-1 shows the available water volume for 2007 by month for river water, spring water, and total water. Flow volumes for April and July 2007 were not available and the values from 2006 are shown. Only the spring water volume was available for August 2007. The spring water sources become notably more important during and after the rainy season because their volume increases significantly. Relying on gravity-fed spring water during as many months as possible allows AMI to save on the cost of pump operation.

The dependence of available spring flow on rainfall is shown in Figure 3-2. Monthly spring flow in 2007 is shown as bars, while average rainfall in millimeters per month is shown by the black line. Rainfall increases during the wet season which runs from May to September. The spring flow increase has a lag of one to two months, as shown by volume increases in July through October. In particular Spring 10 is an important spring, contributing an annual average of 20% the total spring flow volume.

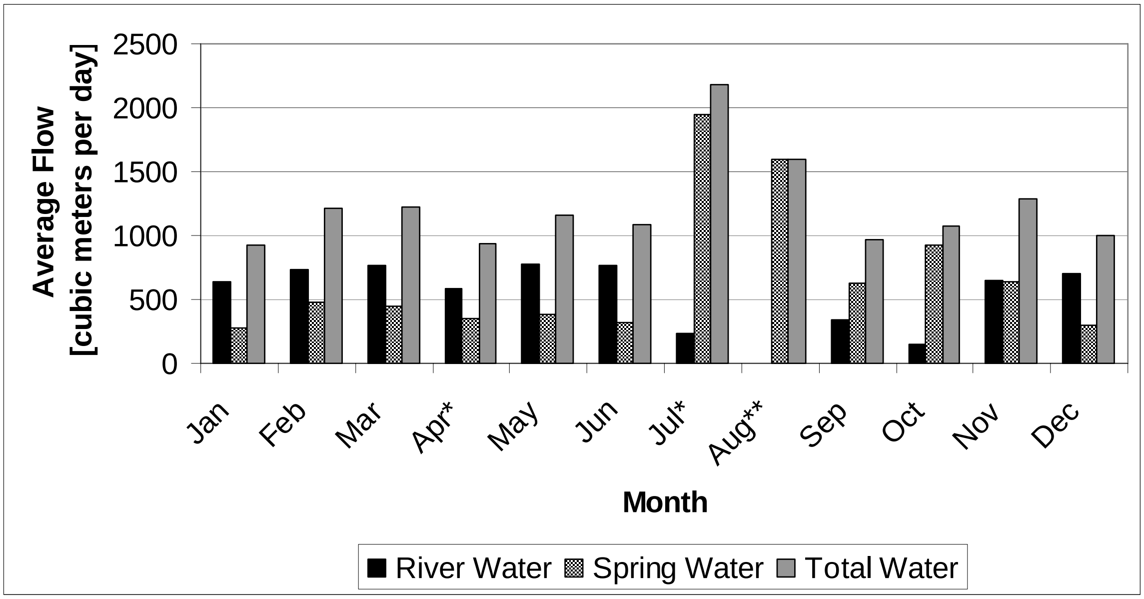


Figure 3-1: Division of 2007 Flow Volume from Storage Tanks by Source
*Data from 2006, ** River Water Flow Rate Unavailable

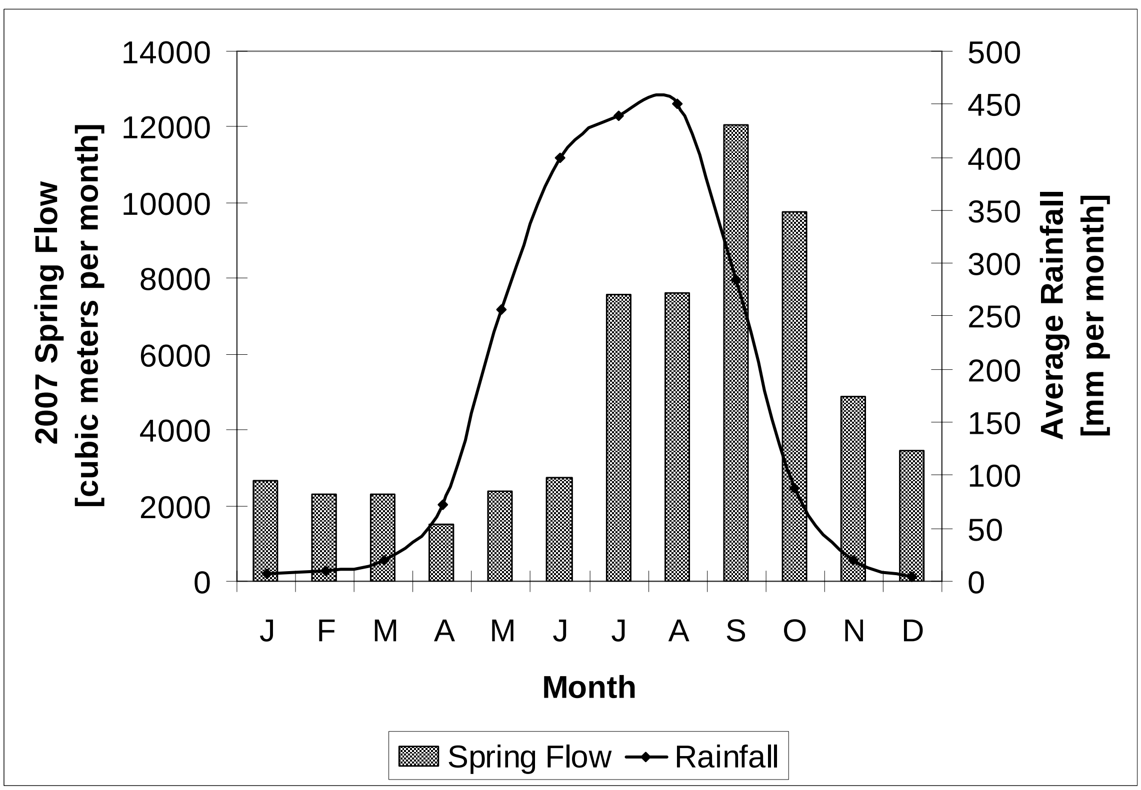


Figure 3-2: Annual Rainfall and Spring Flow Averages (AMI, 2007; GOSIC, 2007).

3.2 Water System Layout

Drinking water in MaeLa reaches over three-fourths of the population through public tap stands after passing through collection systems, pump stations, storage tanks, and distribution networks (Lantagne, 2007). The majority of the remaining fourth of the population gets their water from private sources. The water system was developed over time as the camp grew. This helps account for the many apparently separate systems, some of which were connected after their initial construction. The system is also complicated by the number of sources entering at various points. Some portions of the distribution system are supplied by one source while others are supplied by multiple sources, with annual variability in source ratio based on available water volume.

Water is pumped from the river or is gravity-fed from springs into storage tanks. There are five main tanks which supply the five largest distribution systems in the camp. The tanks are: A Tank, B Tank, C Tank, Christopher Tank, and MOI Tank. Several of the springs, including Springs 6 and 7, 10, 14, and 17, have their own storage tanks as well. The locations of some of these tanks, five of the springs, and the Spring 10 filter are shown in Figure 3-3. The orientation of the image is facing southwest toward the ridge, with the road running along the bottom edge of the image.

Figure 3-3: Major Water System Components.

Spring 10 flows from its source over land into a collection basin and then into a collection structure called Box A. This concrete box contained large (10-25 cm) rocks which were replaced with 2-4 cm gravel in January 2008. From the collection structure the water is piped down a steep slope and passes through a vertical-flow rock filter (VFRF) that has rounded gravel media. After passing through this filter the water is again piped downhill to the HFRF. From the HFRF the water is piped to the SP-10 storage tanks and then enters the SP-10 distribution system and is connected to A Tank. Figure 3-4 is a schematic of the SP-10 collection infrastructure.

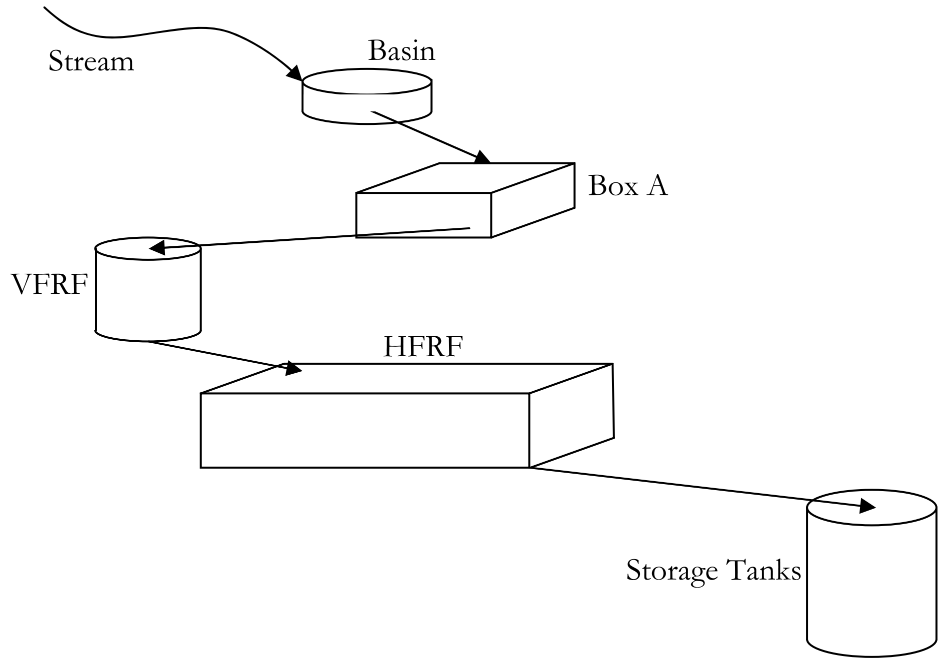


Figure 3-4: Schematic of SP-10 collection infrastructure.

3.3 Water Quality

AMI determines water quality in MaeLa by turbidity measurement, microbial sampling, and chlorine residual testing. Information on turbidity is available for the past several years on a weekly basis at several locations throughout the distribution system. Data on microbial sampling is not available. A surrogate for bacterial contamination is residual chlorine testing which is discussed in Section 3.4.1.

Turbidity of the water supply is measured at a variety of locations throughout the distribution system—including spring collection boxes, storage tanks, and pump stations—normally on a weekly basis. Table 3-1 gives the monthly turbidity average at each of the springs. Values greater than ten NTU are highlighted. Spring 10 is the only spring to have turbidity consistently greater than 10 NTU. In particular, at Spring 10 the highest turbidity can be correlated with the rainy season. Figure 3-5 shows that the turbidity increases over the months of May to September.

Table 3-1: 2007 Monthly Average Turbidity at Springs in NTU.
Highlighted values exceed 10 NTU.

Spring	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SP-2	5	5	5	12	5	5	5	5	5	5	5	5
SP-4	5	5	5	5	5	5	5	5	5	5	5	5
SP-5	5	5	5	5	5	5	5	5	5	5	5	5
SP-6	5	5	5	5	5	5	5	5	5	5	5	5
SP-7	5	5	5	5	7	10	5	5	5	5	5	5
SP-8	5	5	5	5	13	5	5	5	5	5	5	5
SP-9	5	5	5	5	5	5	5	5	5	5	5	5
SP-10	15	13	12	23	67	35	180	44	39	23	48	23
SP-11	5	5	5	5	5	5	5	5	5	5	5	5
SP-12	8	5	5	5	5	5	5	5	5	5	5	5
SP-14	5	5	5	5	5	5	5	5	5	5	5	5
SP-15	5	5	5	5	5	5	5	5	5	5	5	5
SP-17	5	5	5	5	5	5	5	5	5	5	5	5

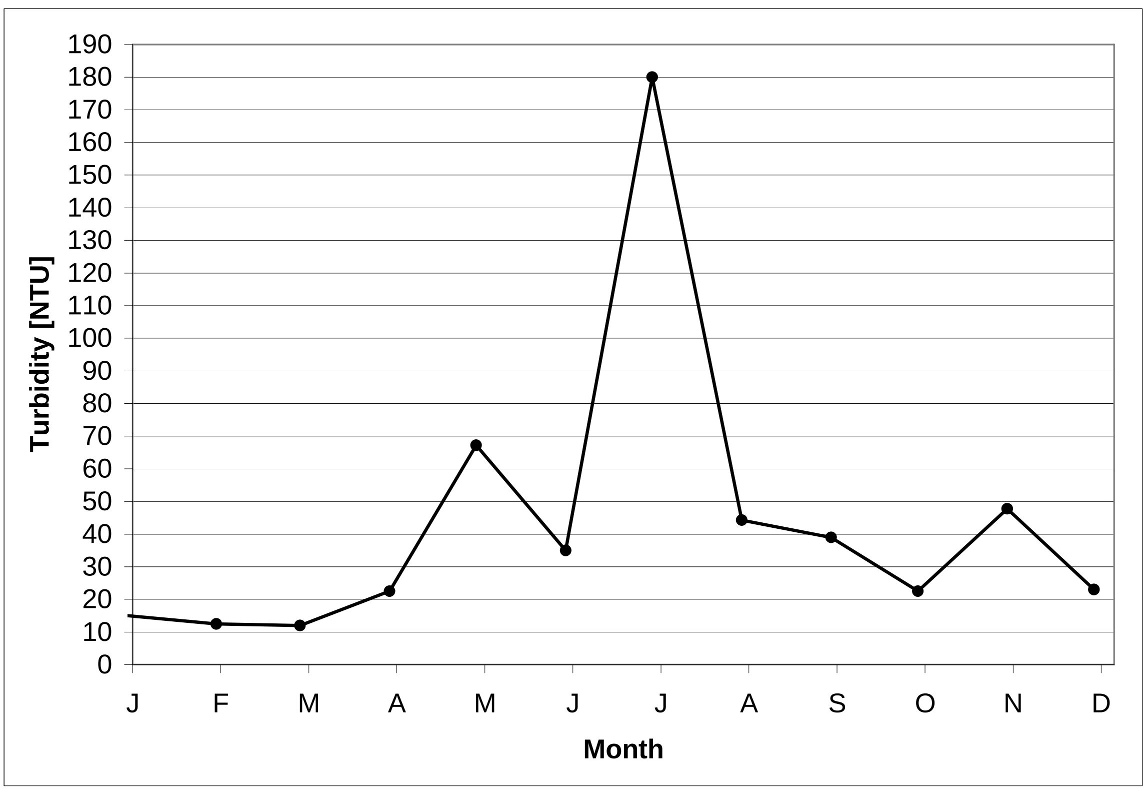


Figure 3-5: 2007 Turbidity at Spring 10.

3.4 Existing Water Treatment

Disinfection is the main form of water treatment to the river and spring water in MaeLa. There is one filter in the system at Spring 10, the location of which is shown in Figure 3-2. As previously noted the main focus of this work is on the water from the springs, of which Spring 10 has been shown to have particularly high turbidity.

3.4.1 Disinfection

Currently, the only treatment for the river and spring water is disinfection by chlorination. Chlorine is a common disinfectant for treatment of water against disease-causing bacteria. According to Lantagne (2007), the distribution system had sufficient disinfection at the tap stands in August 2007.

The maximum disinfection level for chlorine residual (as Cl_2) recommended by the World Health Organization (WHO) is 5 milligrams per liter (mg L^{-1}) and by the US EPA is 4 mg L^{-1} (WHO, 1993; US EPA, 2007). Data for chlorine residual for the first eight months of 2007 are available from AMI. Available chlorine residual measurements have been averaged and are summarized in Figure 3-6. All the values are well below the WHO and US EPA maximum disinfectant levels.

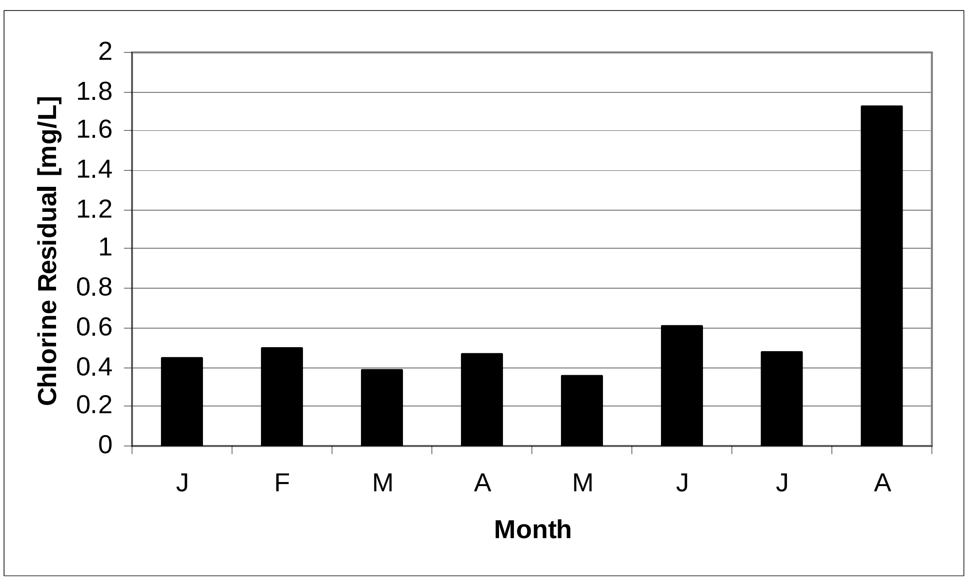


Figure 3-6: Residual Chlorine Levels for January – August 2007 (AMI, 2007).

Chlorination is more effective and lower dosages can be used in low turbidity waters (Sawyer et al., 2003). Since twelve of the thirteen springs maintain low turbidities throughout the year, chlorination of these sources should be effective throughout the year. The variation in the turbidity at Spring 10 requires that the water be treated before it is chlorinated in order to assure the effectiveness of the disinfectant.

3.4.2 Filtration

The only treatment other than disinfection as of January 2008 is a horizontal-flow roughing filter located between the collection and storage of Spring 10 water. The roughing filter has three compartments separated by internal walls constructed with off-set concrete blocks. Figure 3-7 shows one of the internal walls. Each compartment is 4 meters long, 1.5 meters wide, and filled with 0.8 m of filtration media. The media consists of loose gravel with a size range of two to four centimeters.

Figure 3-7: Internal wall of SP-10 HFRF.

A pipe of three-inch diameter conveys water from the SP-10 collection box into the filter as shown in Figure 3-8. This inflow pipe does not distribute the water over the operating width of the filter. The outflow pipe is a vertical perforated pipe that collects water over the depth of the filter and sends it to the SP-10 storage tank through an outlet located at the bottom of the HFRF. Chapters 5 and 6 contain further information on the operation and maintenance of the filter.

Figure 3-8: Inflow pipe to SP-10 HFRF.

The purpose of the filter is to maintain a consistent turbidity at SP-10, since there is an annual increase in turbidity during the rainy season. Figure 3-9 shows the turbidity increase at SP-10 collection Box A and the turbidity of the water at the SP-10 storage tank after passing through the HFRF. The filter achieved the treatment goal of less than 10 NTU on average for seven of the twelve months in 2007.

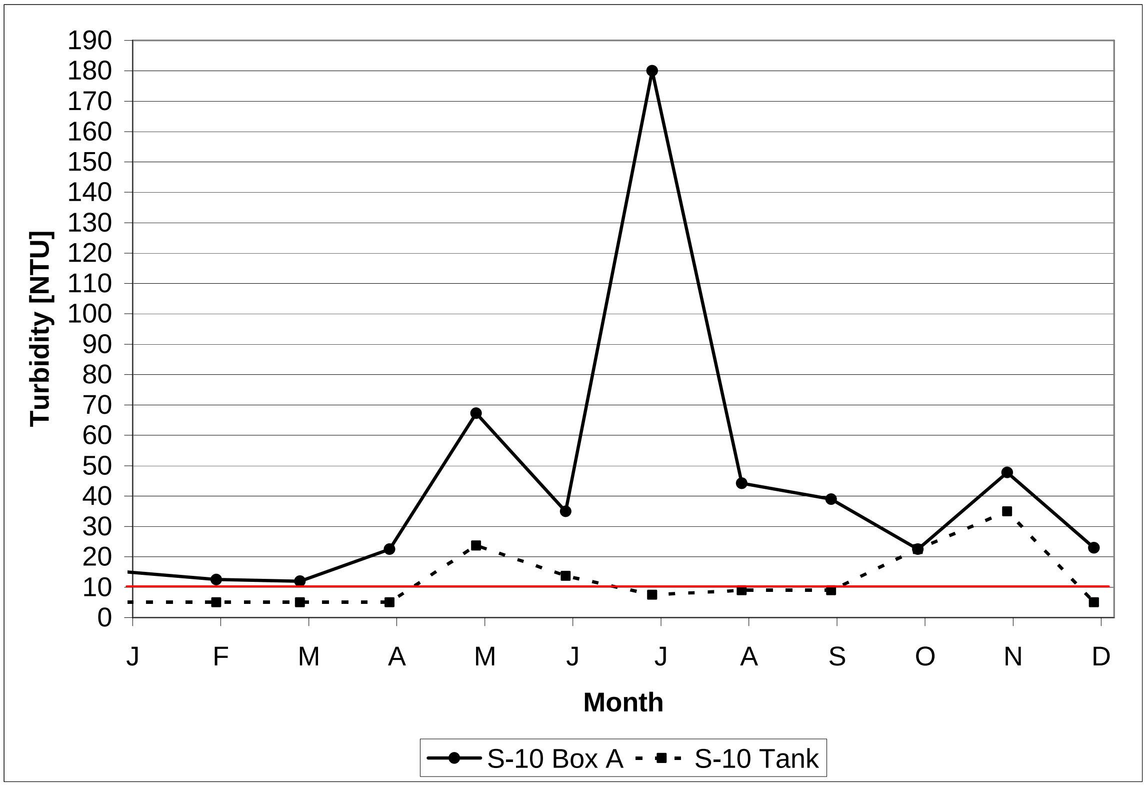


Figure 3-9: 2007 SP-10 Turbidity at collection Box A and at storage tank.
The HFRF operates between these two sampling points.

4 SPRING WATER QUALITY IMPROVEMENT

Spring water is an important water source for MaeLa. It accounted for an average of 50% of the water supply in 2007 and climbed to 80% of the water supply during the rainy season. Monthly flow volumes are shown in Figure 3-1. The spring water in MaeLa presents several water quality issues because of the number of springs and the annual water quality cycle. This chapter first describes the water treatment design parameters and treatment objectives specific to MaeLa. Then potential water quality improvement technologies are discussed. Data from previous studies and recommended values of design variables are included.

4.1 Design Parameters

Water treatment design is based on influent water quality and treatment objectives. Based on the existing information about spring water quality in MaeLa, four main design parameters have been identified. Turbidity is the parameter of most interest because the effectiveness of disinfection by chlorination is lowered at higher turbidity (AWWA, 2003; Wegelin et al., 1991). The water from the largest volume springs is chlorinated before release into the distribution system. The bacterial load of the water is the second important parameter because of the potential for disease-causing organisms in the water supply, particularly in the sources that are not chlorinated. The last two design parameters have to do with the size and location of the spring, both of which are unique to MaeLa due to seasonal flow variation and steep land slopes.

4.1.1 Turbidity

Turbidity is mineral and organic particulate matter in water that causes light absorption and scattering (Eaton et al., 2005). The type of particulate matter varies for each different water (LeChevallíer et al., 1981). Turbidity reduces aesthetic acceptability, filterability, and disinfection potential of drinking water (Sawyer et al., 2003). Nephelometric turbidity units (NTU) are the standard unit for turbidity measurement. As demonstrated in Chapter 3, the turbidities at the springs are less than ten NTU except at SP-10 where turbidities have an annual variation.

The types of pre-treatment and treatment units are determined by the turbidity of influent water. Okun and Schulz (1984) write that water greater than 50 NTU requires pre-treatment. This indicates that the technologies discussed below under the heading of pre-treatment are applicable to MaeLa, because turbidities spike above 50 NTU during the rainy season and can also reach 50 NTU in the dry season.

The impact of turbidity on chlorination is the main reason to achieve consistent, low turbidity. LeChevallíer et al. (1981) found that the threshold of effectiveness of chlorination was exceeded in surface waters with turbidity between six and eight NTU. The results of the study, which was conducted in four different watersheds, are shown in Figure 4-1. The water samples depicted in Figure 4-1 were from Oregon, USA. Wegelin et al. (1991) recommend low turbidity water for efficient disinfection via chlorination, but do not specify a value of turbidity. Based on the accuracy of turbidity measurement in MaeLa, as detailed in Chapter 6, I determined a treatment goal of less than ten NTU for the spring water sources. This agrees with the current treatment goal of AMI.

The field work results discussed in Chapter 5 demonstrate that chlorination is effectively used as a disinfectant in MaeLa. In order to reduce chemical requirements and simplify chlorine application, producing a consistently low-turbidity water source through pre-treatment is desired.

4.1.2 Bacterial Loads

Water-borne bacteria transmit a range of diseases, which treatment aims to reduce or eliminate by removing bacteria from the water. Total coliform and *Escherichia coli* (*E. coli*) are used as indicators of the presence of water contamination from bacterial load (Alekal et al., 2005). The goal of the treatment units in combination with disinfection is elimination of bacteria from the MaeLa water supply.

The water quality standards for Thailand are 2.2 total coliform per 100 mL and zero *E. coli* per 100 mL (Okun and Schulz, 1984). These are less stringent than the US standards, which are 0 per 100 mL for both total coliform and *E. coli* (US EPA, 2007). Although chlorination produces a water low in bacterial contamination, filtration in combination with disinfection will produce an even higher quality effluent as demonstrated by chlorine effectiveness at lower turbidities (LeChevallíer et al., 1981; Lantagne, 2007).

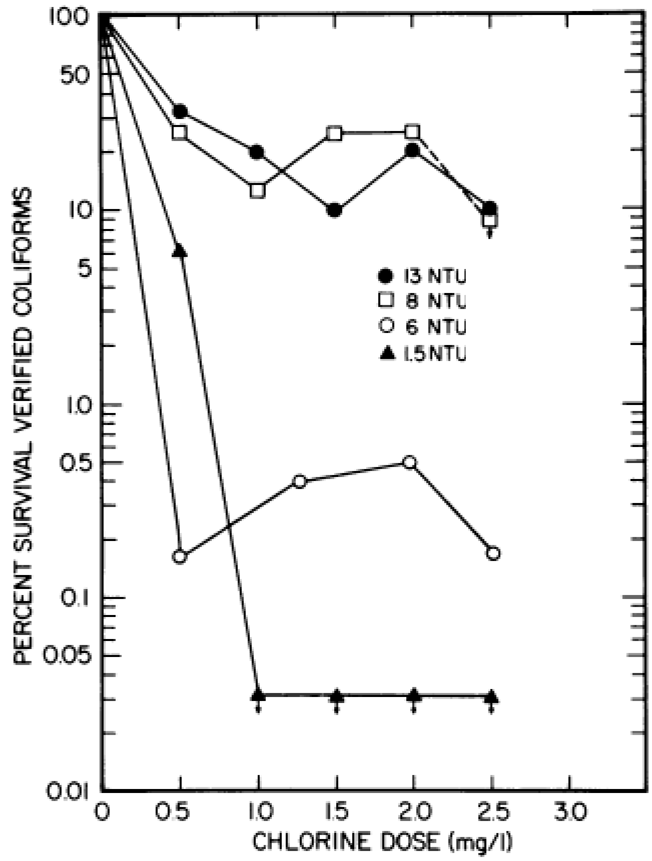


Figure 4-1: Surviving coliforms as a function of influent turbidity and chlorine dose (LeChevallíer et al., 1981).

4.1.3 Site Specific Parameters

Some of the design parameters for water treatment processes are specific to the location of the treatment system. For MaeLa the annual water volume variation and available land area are the two main site-specific parameters. First, the available water has annual volume variation. The flow from each source for the past three years is available from AMI (2007). The volume of water is correlated to the annual rainfall, with an increase in available water volume beginning in July and continuing through October. This is shown in Figure 3-2. During the July-October wet season the flow volume more than doubles. Any treatment process will need to be able to handle this seasonal variation.

Second, the locations of the springs present a design restriction. The springs are at elevation above the camp where there is little flat land on which to construct treatment units. The elevation change across the camp limits the land available to build water treatment units.

The system is gravity-fed, which if at all possible should be maintained to minimize fuel costs associated with pumping. This means the treatment units will need to be located at a high elevation. The springs flow near the top of the ridge and the storage tanks are also located at this elevation. AMI has records of the land area available at each of the springs. The area needed for the treatment units is dependent on the processes selected and the volume of water to be treated.

4.2 Pre-treatment

Design of treatment facilities is dependent on several variables including treatment objectives, influent water quality and flow volume, availability of materials and land, and ability to perform technical maintenance (Okun and Schulz, 1984). As described above, the main goals of treatment are to remove turbidity and bacteriological contamination and to normalize the quality throughout the year. Due to the range of turbidity seen in Table 3-1 and Figure 3-4, some sort of pre-treatment is recommended (Okun and Schulz, 1984). Wagner and Lanoix (1959) write that the simplest technologies are the best because of low maintenance requirements. This is particularly important in MaeLa, where the availability and turnover in maintenance staff predicates low maintenance.

Pre-treatment describes several low-technology processes that improve water quality without significant labor or mechanical investment (Wagner and Lanoix, 1959). The influent water quality and quantity dictate the type of pretreatment. Okun and Schulz (1984), Wegelin (1996), and Wegelin et al. (1991) describe the pre-treatment selection based on influent turbidity. This is summarized in Table 4-1.

4.2.1 Plain Sedimentation

Plain sedimentation uses gravity settling at moderate flow rates to remove particulate matter, producing an effluent with lower suspended solids content than the influent (Okun and Schulz, 1984). Compared to full-scale sedimentation, the surface loading rate is increased in plain sedimentation. The result is a lower residence time for water in this process compared to treatment sedimentation. Plain sedimentation is effective at removing mineral particles of greater than ten-micrometer diameter (Okun and Schulz, 1984). This means that influent water from surface sources is most effectively treated in plain sedimentation units.

Table 4-1: Pre-treatment based on Influent Turbidity
(Okun and Schulz, 1984; Wegelin, 1996; Wegelin et al., 1991).

Pre-treatment Type	Influent Turbidity
Plain Sedimentation	20-100 NTU
Storage	> 1000 NTU
Vertical-Flow Roughing Filter	20-150 NTU
Horizontal-Flow Roughing Filter	20-1000 NTU

4.2.2 Storage Tanks

Storage tanks, often uncovered, function similarly to plain sedimentation units. The main difference is that the residence time of water in storage units is longer. Storage lowers turbidity and bacterial loads (Okun and Schulz, 1984; Hofkes, 1983). Additionally, storage tanks at the beginning of the treatment train can be used to time-release influent spikes in the water supply that occur during the rainy season.

4.2.3 Roughing Filtration

Roughing filtration uses the principles of sedimentation and sorption that drive filtration, but with larger filtration media. This is the most effective pre-treatment unit when pre-treatment is combined with slow-sand filtration (Okun and Schulz, 1984). The two types of roughing filtration are vertical-flow and horizontal-flow. Vertical-flow allows for higher filter rates, but the water depth in the unit is limited. Vertical filters are also classified by their flow direction into up-flow and down-flow filters. Horizontal-flow units have long lengths which allow for low filter flow rates. Both types can be manually regenerated, reducing the mechanical demands that may be required if backwashing is used (Okun and Schulz, 1984). Figure 4-2 shows a basic schematic of each of the three types of roughing filters.

Both flow orientations have successful implementations in Thailand. One horizontal roughing filter removed 60-70% of turbidity in influent water with 30-100 NTU (Okun and Schulz, 1984). Okun and Schulz (1984) also refer to a vertical roughing filter that proved to be even more effective, reducing influent turbidity of up to 150 NTU to less than 5 NTU, while also removing 60-90% of bacteria. This filter used shredded coconut husks as the filtration medium. HFRF have been shown by various studies to remove turbidity, iron, algae, and total coliforms and other bacteria.

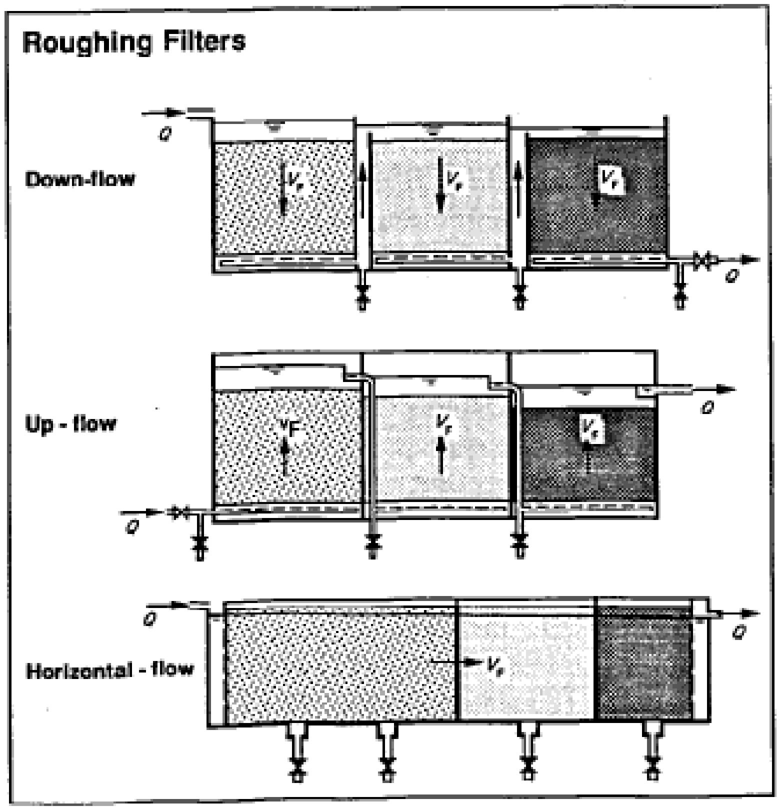


Figure 4-2: Roughing Filter Schematics
(Wegelin et al., 1991).

Based on the flow volume, influent water quality, and land restrictions, roughing filtration is the most applicable pre-treatment process at MaeLa. In addition, a HFRF is already in operation at SP-10, providing invaluable existing knowledge in the camp of the operation and maintenance of this type of pre-treatment technology.

4.2.3.1 General HFRF Design

HFRF consists of an inflow control, an inflow distribution device, the filter, an effluent collection device, an outlet control, and a drainage system (Wegelin, 1996). A general HFRF layout is shown in Figure 4-3. The filter itself can be divided into three or four compartments with graded gravel filter media (Wegelin et al., 1987). The outlet control should be placed at the top of the filter in order to maintain a constant volume of water in the filter (Wegelin et al., 1987; Sittivate, 2001). Table 4-2 shows general filter dimensions from Wegelin et al. (1987) and Collins et al. (1994).

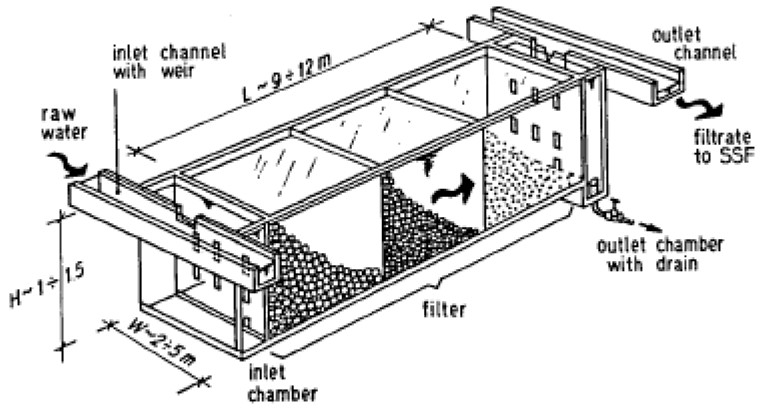


Figure 4-3: General Layout of a Horizontal-Flow Roughing Filter (Wegelin et al., 1987).

Table 4-2: General HFRF Dimensions (Wegelin et al., 1987; Collins et al., 1994).

Dimension	General Value [m]
Length	6-12
Width	2-4
Height	1-2

4.2.3.2 HFRF Media Size

A variety of media have been tested for effectiveness in HFRFs. Locally available materials such as coconut husks and burnt bricks have been studied in the past. The existing HFRF in MaeLa uses coarse gravel. This section only discusses gravel, because it is the most commonly used medium and is currently used in MaeLa. In addition, El-Taweel and Ali (1999) found gravel to be the most effective medium while comparing six different media combinations.

The most common media size range is from 0.3 cm to 5 cm. Often three differently sized media are used in combination to achieve even better results. Table 4-3 summarizes the effective gravel medium sizes found by different research.

Table 4-3: HFRF Medium Size Ranges

Range of Gravel Size [cm]	Source
0.3 – 4	Logsdon et al., 2002
0.3 – 3.5	Jayalath et al., 1995
0.4 – 2	Wegelin et al., 1987
0.5 – 5	Boller, 1993
1 – 2	Sittivate, 2001

4.2.3.3 HFRF Filtration Rate

A range of filtration rates is discussed in the literature and their variability is based on desired treatment rate and filter performance. Lower filtration rates are directly related to higher particle removal. Often, though, the demand for water does not allow filters to be operated at the lower bound of designed flow rates. Table 4-4 summarizes a range of filtration rates and, if available, their performance.

Table 4-4: HFRF Filtration Rate Ranges and Associated Performances.

Filtration Rate [m hr^{-1}]	Performance [% Reduction]	Parameter	Source
0.3	90%	Turbidity	Sittivate, 2001
0.3 - 1.5	50 – 70%	Solids content	Wegelin, 1996
0.3 – 1.5	> 90%	Turbidity	Wegelin, 1996
0.3 – 1.5	--	--	Collins et al., 1994
0.3 – 1.5	--	--	Logsdon et al., 2002 from Hendricks, 1991
0.5 – 2	--	--	Boller, 1993
0.5 – 4	--	--	Wegelin et al., 1987
1 – 2.5	50 – 60%	Turbidity	Jayalath et al., 1995
1 – 5	--	--	Wegelin, 1996 for "Rock filter"
1.5	40 – 100%	Turbidity	Lin et al., 2006
4.5	40%	Turbidity	Jayalath et al., 1995

4.2.3.4 HFRF Maintenance

Maintenance of any treatment unit is important to ensure continuous effective treatment. The frequency of cleaning the filter media is dependent on the influent water quality, but is generally every two to three months for HFRF (Hofkes, 1983; Wegelin et al., 1991). Cleaning can be achieved mechanically by flushing the compartments with a large volume of water over a short time or manually by removing the filter media, cleaning it, and replacing it.

Wegelin (1996) found that hydraulic cleaning is more effective than manual cleaning if the necessary flow rate can be achieved. A flushing flow rate of at least 30 m hr^{-1} is needed and ideally it would be 60-90 m hr^{-1} (Wegelin, 1996). In order to achieve media regeneration with mechanical washing, the flush flow rate must be achievable. This is dependent on several factors, including: available flow to achieve the flushing flow rate, outlet area for drainage, and wash water volume. The outlet area for drainage should be made as large as possible, as it is often the limiting parameter in reaching the desired flow rate (Wegelin, 1996).

It is recommended to have two HFRF so that maintenance can be completed while the other filter is in use (Wegelin and Mbwatte, 1989 and Wolters et al., 1989 in Logsdon et al., 2002).

4.3 Additional treatment processes

Previous study shows that roughing filtration (RF) can achieve the treatment goals of spring-water quality without the need for additional treatment processes. Further processes, such as slow sand filtration, require exact technical design and regular maintenance. Since roughing filtration will meet the needs of the spring water and is compatible with current staff availability, it is recommended to focus on RF as the applicable technology for MaeLa.

Another benefit of the implementation of RF within the camp is the capacity to add additional treatment processes as necessary. As Okun and Schulz (1984) note, roughing filtration is the most effective pre-treatment process to be used in series with slow-sand filtration. If AMI chooses to expand treatment of the spring water, the effective implementation of roughing filters in the camp will mean that the influent water quality necessary for slow-sand filtration is already being achieved.

5 FIELD WORK

Information on the condition of the existing spring collection and treatment infrastructure was gathered on a site visit to MaeLa Temporary Shelter in January 2008. Water turbidity at Spring 10 (SP-10) was measured several times at various locations. Flow rate tests were conducted at the SP-10 filter. Microbial sampling took place at ten places throughout the system.

5.1 Turbidity

As discussed in Chapter 3, SP-10 is a significant source of water for the camp, particularly in the rainy season. In addition, its water quality is among the most variable, with rainy season turbidities that are 5 to 10 times higher than those during the dry season. Measuring turbidity at SP-10 served three purposes. First, it determined some dry season turbidity levels. Second, it helped understand which existing treatment processes are removing turbidity under dry and simulated-rainy season turbidity. Third, it compared turbidity measurement techniques used by AMI.

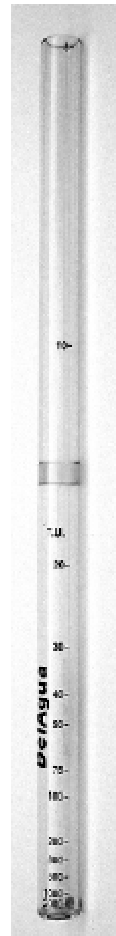
5.1.1 Measurement Methods

Turbidity was measured using a Hach 2100 turbidimeter. The Hach turbidimeter is an electronic nephelometer that measures the scattering of incident light (Eaton et al., 2005). This is the standard method of measuring turbidity.

The turbidimeter was calibrated on arrival and once weekly for the remainder of the visit. Measurements were taken immediately after collection so that the temperature and pH did not change significantly before the measurement was recorded. Sample vials were cleaned with silicone oil before each measurement in order to reduce measurement interference from the glassware (Eaton et al., 2005).

AMI measures turbidity with two different methods. The first is using a LaMotte 2020 series electronic nephelometer. The second, and more commonly used in practice, is with a turbidity tube. This device is a plastic tube of one-inch diameter, into the bottom of which a ring or other pattern is etched. The user pours water into the tube until the etching is no longer visible. The water level in the tube gives the turbidity as read from gradations on the outside of the tube. Figure 5-1 shows both measuring devices.

(a)



(b)

Figure 5-1: Turbidity measuring devices.
(a) electronic nephelometer and (b) turbidity tube.

The same sampling and cleaning procedure was used for both the electronic nephelometers. The LaMotte turbidimeter was calibrated prior to use. The turbidity tube was used with standard procedures.

Turbidity was measured at eight locations along SP-10 from its origin surface flow to the filter outflow. Measurements were made a second time at five of these locations. During the simulated rainy season flow test, the turbidity was recorded at four locations along SP-10.

5.1.2 Observations

SP-10, including collection Boxes A and B and the filter, is in a wooded area where there is little direct light penetration at the ground level. This is of direct concern when using the turbidity tube, as it is necessary to have strong sunlight to use the instrument correctly.

5.2 Filter Flow Tests

The SP-10 roughing filter consists of three compartments each with the same filter material. Upon first inspection, the free surface of the water was above the filter media in the first and third compartments. The filter media in the second compartment had a layer of sediment on top of it. The construction of the filter, without inlet or outlet weirs, suggested that short circuiting could be occurring. Figure 5-2 shows the plan layout of the filter, including the walls separating the three compartments. These walls are made of offset cement blocks. The theoretical flow path is shown with dashed arrows. Potential short circuits are shown by the arrows. The inflow is a pipe through which water free-falls onto the filter media and the outflow is a vertical pipe which is perforated over depth. To determine the residence time of the filter under different conditions, three tracer flow tests were conducted under varying filter and influent water conditions.

5.2.1 Measurement Methods

The tracer tests were conducted by adding a spike input of saline solution to the inflow and recording the conductivity of the filter effluent. The saline solution was 500 mg of salt dissolved in five liters of water. Before adding the saline solution, a background conductivity reading was taken at the filter outflow. The salt water was added and conductivity was measured at the outflow until the conductivity spike passed and background conductivity was re-established. The conductivity was measured with a Hanna Instruments 9812 pH/EC/TDS meter. The device was calibrated for conductivity prior to every test.

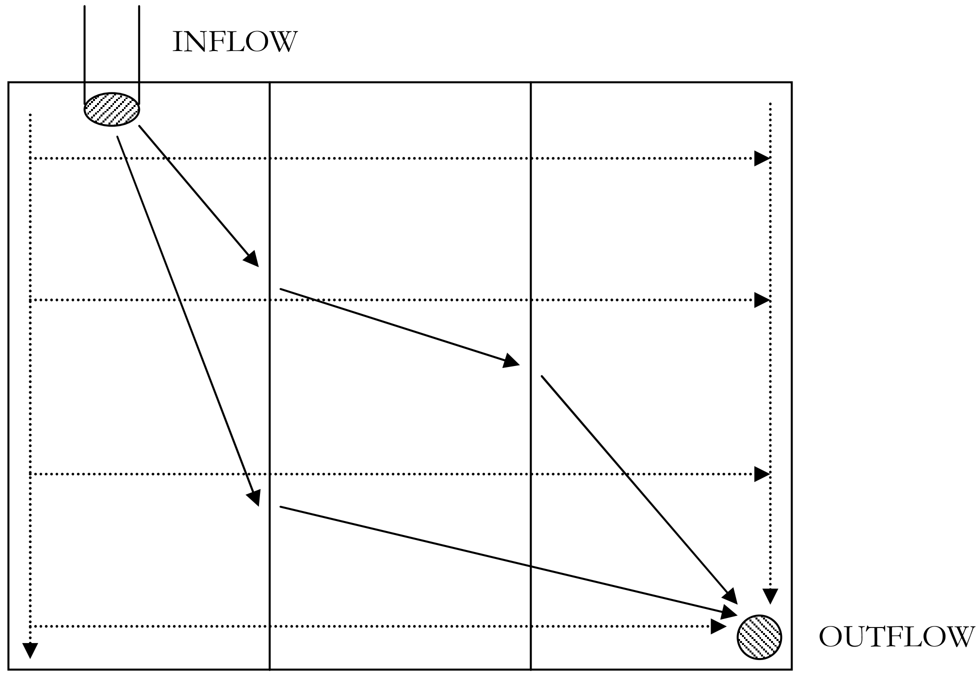


Figure 5-2: Spring-10 Roughing Filter Flow Paths.
Theoretical paths are shown with dotted-line arrows and
potential short-circuiting paths are shown with solid-line arrows.

5.2.2 Observations

The inflow of the filter is a point source instead of a more traditional weir that would distribute flow over the width of the filter. The saline solution was dumped into the inflowing water stream, so it too was not distributed over the width of the filter. This mode of tracer solution input is consistent with the normal inflow and thus a better representation of the filter flow path than an attempt to distribute the solution over the width of the filter would have been.

The conductivity was measured near the top of the free surface of the water. The data do not represent the vertical distribution of saline solution found at the outflow.

5.3 Microbial Sampling

Various references note the potential for bacterial load reduction by roughing filters. In order to get an idea of the background quality of the influent and effluent water quality at SP-10 filter, microbial testing was conducted. Samples were also taken at several taps and storage tanks to assess the effectiveness of disinfection and the quality of water being provided to the consumers.

5.3.1 Measurement Methods

The microbial testing selected *Escherichia coli* (*E. coli*) and total coliforms. *E. coli* is a disease-causing organism and total coliform are used to indicate the possible presence of disease-causing strains. Samples were taken at the inflow and outflow of SP-10 filter, MOI Tank, Christopher Tank, SP-14 Tank, C Tank, SP-10 Tap 5, SP-17 Tap 13, B Tank Tap 4, and A Tank Tap 7.

Samples were collected and de-chlorinated in 100 mL sample bags using sodium thiosulfate (US EPA, 2003). Total coliform and *E. coli* were tested for using the standard plate count method. The medium was Violet Red Bile, pre-measured on 3M® Petrifilm® Coliform/*E. coli* plates (3M, 2001). Dilution and incubation occurred within eight hours of sample collection. Each sample had three dilutions: 1:1, 1:10, and 1:100. These dilutions provided internal quality control as well as additional data (Eaton et al., 2005). Incubation took place at 35 degrees Celsius for 24 ± 2 hours. The plates were counted with a lighted hand lens.

5.3.2 Observations

A total of 16 samples were plated at the three specified dilutions with duplicates of each dilution. These 16 samples included six duplicate samples, which were from each of the taps and the SP-10 filter collection points. Only one sample was taken at each of the tanks.

6 RESULTS

Flow tests, turbidity measurements, and microbial sampling at the SP-10 filter provide information about the effectiveness of the existing treatment and the potential for performance improvement. Modifications made to the roughing filter during the field visit improved the filter performance and confirmed that the water was short circuiting through the media. Microbial samples taken across the camps showed broadly that chlorination is an effective disinfection technique for the camp.

6.1 SP-10 Cleaning and Baffle Addition

Upon arrival in MaeLa, the SP-10 horizontal flow roughing filter (HFRF) needed to be cleaned and the volume of filter media needed to be restored. The free surface of the water was visible in two of the three compartments of the filter. The other compartment had a visible layer of sediment on top of the filter media. The filter was cleaned during the second week of field work. In addition, gravel was added to the first and third compartments so all the water now flows below the surface of the medium.

Day laborers hired by AMI clean the filter by hand. The gravel is removed from each compartment and the influent water is diverted over the dirty gravel. Gravel is cleaned by the basketful and returned to the filter. The process is shown in Figure 6-1.

While the gravel was removed from the filter, two baffles were added in order to direct flow through the entire filter volume. Each baffle consisted of a plastic sheet placed over a portion of the cinder-block interior wall. The layout of these baffles is shown in Figure 6-2. The results of this modification are discussed in the following sections on turbidity and flow testing.

6.2 Turbidity

Turbidity was used to demonstrate the effectiveness of various roughing filters along the pipe that runs from SP-10 Box A to SP-10 storage tanks. As described in Chapter 3, there are two rock VFRFs which precede the main SP-10 HFRF. Both of these small filters have larger-diameter filter material than the HFRF. The materials are described in Table 6-1.

Figure 6-1: Cleaning the HFRF media.
(L) Shows the gravel removed from the filter, (R) show the workers cleaning a basketful of gravel with the diverted water supply.

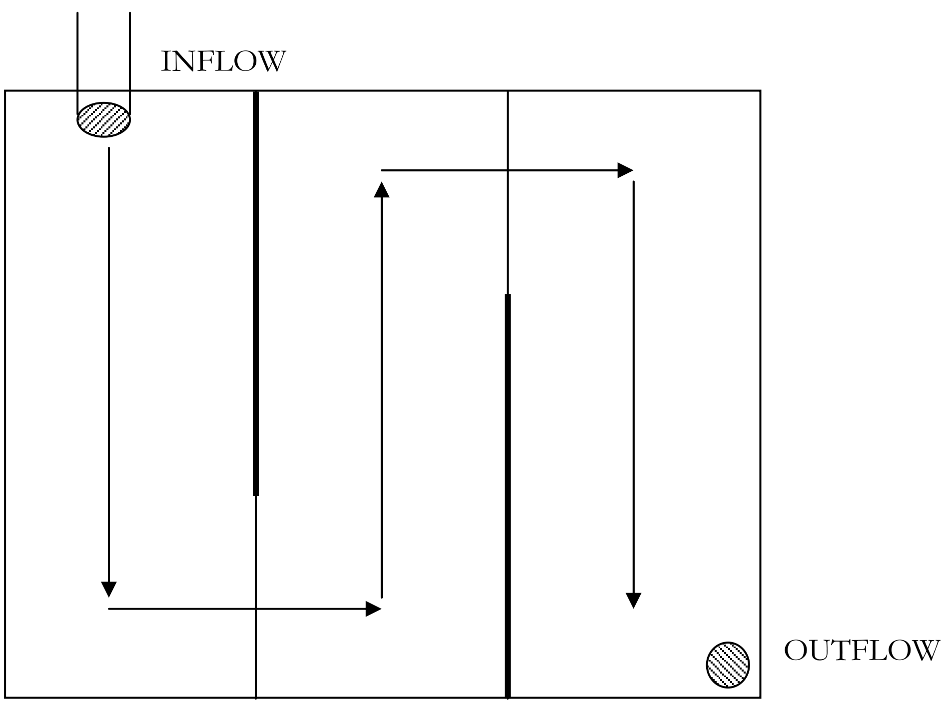


Figure 6-2: Plan View of Spring-10 Roughing Filter Flow Path with Baffles.
Baffles are shown in bold and coincide with the compartment walls.

Table 6-1: SP-10 Treatment Processes.

Filter	Media Material	Media Diameter [cm]	Filter Length [m]
Box A	Large stones	10 – 30	1
VFRF	Rounded stones	4 – 8	1
HFRF	Coarse gravel	1 – 4	12

6.2.1 Results

The short length and large media in Box A and the VFRF predict that neither is effective at removing turbidity from the water. Turbidity was sampled twice at multiple points along the collection pipe. The results are shown in Figure 6-3. The first set of data was taken before the HFRF was cleaned, while the second set was collected after cleaning. Both sets are under natural environmental conditions for January, which falls in the dry season. Stream 1 and Stream 2 are two sample points in the SP-10. The relative locations of all these sample points are described in Chapter 3 and shown in Figure 3-4.

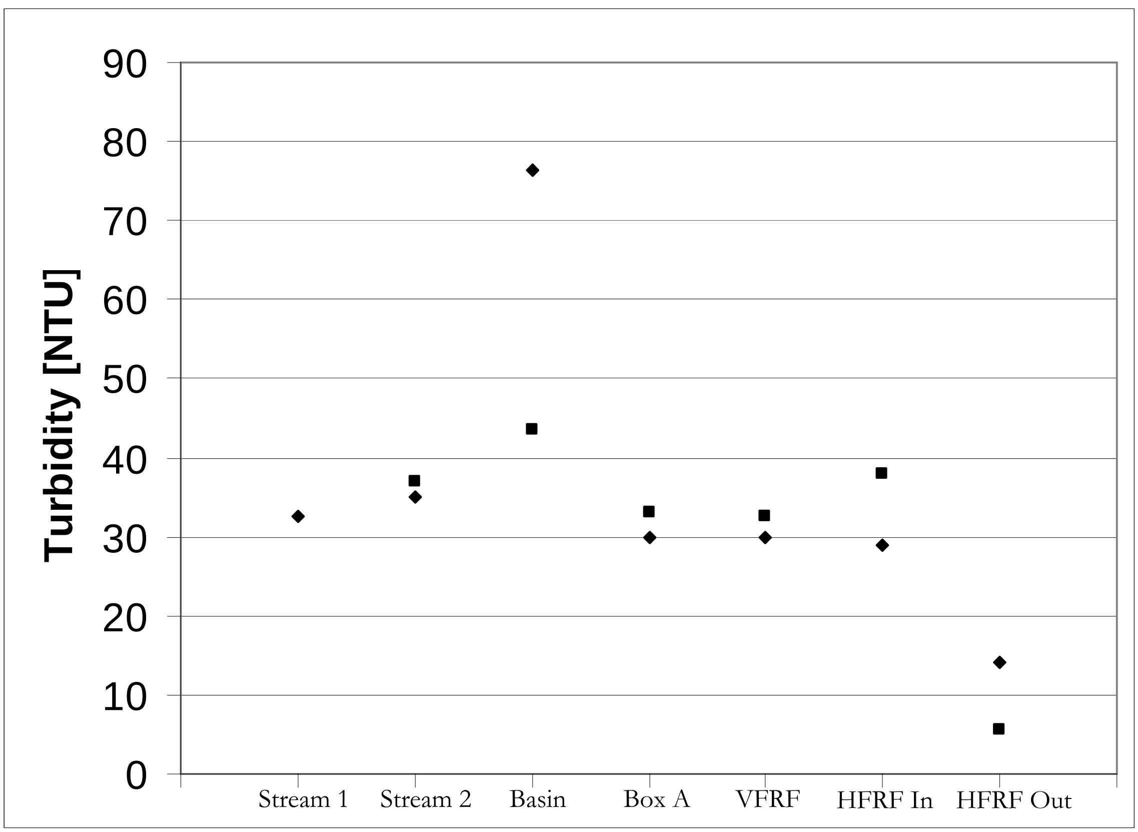


Figure 6-3: Turbidity along SP-10 collection infrastructure.
Diamonds show turbidity prior to HFRF cleaning,
squares show turbidity after HFRF cleaning.

The turbidity in the stream and collection basin is between 30 and 40 NTU, with one spike to above 70 NTU. From Box A through the HFRF inflow, the turbidity is again between 30 and 40 NTU, but usually nearer to 30 NTU. The HFRF is the only treatment process that removes a significant amount of turbidity. In the first case, when the filter was not cleaned and had not been modified, more than 50% removal was achieved. In the second case, when the filter had been cleaned and the baffles added, more than 85% removal was achieved. In the second case the treatment goal of producing an effluent with 10 NTU or less was also met.

Two conclusions can be drawn from these results. First, neither Box A nor the VFRF is treating the water. The treatment is all achieved in the HFRF. Second, the clean, modified filter is more effective than the dirty, unaltered HFRF. This result is discussed further with respect to water residence time in the filter in Section 6.3.

6.2.2 Sampling Technique Comparison

During the second turbidity sampling, values were taken with the Hach turbidimeter as well as with two devices AMI uses regularly for turbidity measurements. The first is an electronic nephelometer made by LaMotte. The second method is a turbidity tube. All the data reported in this document were taken with the calibrated Hach turbidimeter. The data in this section were taken only for instrument comparison and not used as additional data in this thesis.

The results of this duplicate sampling are shown in Table 6-2. The calibrated Hach turbidimeter results differ by 50-200% from the devices AMI uses to measure turbidity. The LaMotte turbidimeter had not been calibrated recently enough for the AMI staff to remember. It was calibrated with four solutions on the day these data were collected, but its precision even just after calibration was not good. More accurate and precise results could be found by improving sampling techniques and regularly performing maintenance and calibration on the LaMotte turbidimeter.

According to the manufacturer, the turbidity tube should be used in the shadow of the measurer while they stand in direct sunlight. All of the SP-10 collection pipe and filters are in a wooded area. The only place it was possible to take readings in the sun was about five meters away from the HFRF. This presents a problem because the stream, Box A, and

VFRF are all far enough from direct sunlight that sampling cannot occur immediately. A sample would have to be collected for later analysis and carried down the hill to the edge of the woods. It would be more practical to carry the LaMotte turbidimeter, which can be used under tree cover.

Table 6-2: Turbidity by location and measurement device.

Location	Hach Turbidimeter	LaMotte Turbidimeter	Turbidity Tube	Lighting
Stream	37	21	75	Shade
Collection Basin	44	25	75	Shade
Box A	33	22	50	Shade
VFRF	33	19	40	Shade
HFRF Inflow	38	22	40	Shade
			25	Sun
HFRF Outflow	6	4	10	Shade
			< 5	Sun

The LaMotte turbidimeter needs regular calibration and maintenance for it to be reliable. In January there were only two calibration solutions present in the instrument case. At least three solutions should be used for calibration, which should be completed weekly in order to ensure consistent instrument function.

6.3 Filter Flow Tests

Upon observation of the HFRF design, short-circuiting of the media was a concern. In order to understand the flow of water through the filter several tracer tests were conducted. The first test was completed before the filter was cleaned or modified as discussed in Section 6.1. The second test was completed after the filter was cleaned and the baffles were added.

6.3.1 Theoretical Residence Time

The filter residence time is a function of the filter volume and the flow rate of water through the medium, which has a specific porosity. Ideally the water will be in the filter for the theoretical residence time, so that the most treatment can occur. The filter volume, V, and the flow rate, Q, are related by the porosity, n, to residence time, t_R, as shown in Equation 6-1.

$$t_R = n\frac{V}{Q} \qquad \text{Eq. 6-1}$$

The volume of the filter is 15 m^3. The flow rate in January 2008 was 0.1 m^3 min^{-1}. The coarse gravel has a porosity of approximately 0.5 (MWH, 2005). Using Eq. 6-1, the residence time of the filter is 75 minutes.

One of the reasons for the baffle addition is to increase the utilization of the entire filter volume, therefore increasing the average residence time of water in the filter. These results are discussed in the following section.

6.3.2 Tracer

A saline tracer was used to determine the impact of the baffles on the residence time in the system. The tracer was composed of 500 g of salt dissolved into five liters of water. The resulting salinity is about 100,000 ppm and the density is 1075 kg m^{-3}, versus approximately 1000 kg m^{-3} for the otherwise fresh water in the filter. Thus, the denser salty water can be expected, at least in part, to settle to and travel along the bottom of the filter. Since the tracer and water do not necessarily follow the same travel path, the experimental results of tracer test residence time in the HFRF cannot be directly compared to the HFRF residence time of 75 min. The results of the tracer study can be used to compare relative residence time increase after the installation of the baffles.

6.3.3 Results

The results of the tracer tests are divided into two sections, one for the two tests run with dry season turbidity and the other for the test run with simulated-rainy season turbidity. The results demonstrate that the baffles increased the residence time of water in the filter by approximately three times and that the clean HFRF is capable of greatly reducing even high turbidity loads. The measured times cannot be equated to the filter residence time because of the density difference between the tracer and the water.

6.3.3.1 Dry Season Load

The mean residence time of the tracer in the first test was about 30 minutes. This test established a background to which the post-baffle installation tracer test could be compared. Although the exact relationship between the flow velocity of the tracer and the water is not known, such a low tracer residence time likely indicates short-circuiting of the filter. This means that the treatment potential of the filter was not maximized.

The second test results showed the residence time of the tracer to be about 95 minutes. This test was conducted after the baffles were installed, demonstrating that this simple installation increased the functionality of the HFRF. The relative residence time of water in the filter increased three times after installation of the baffles. Figure 6-4 shows the data for both the tests. The residence time for the tracer found in these studies is not the residence time of the filter because of the density difference between the tracer and the water. The tracer residence time is about 20 minutes longer than the theoretical residence time of water in the filter.

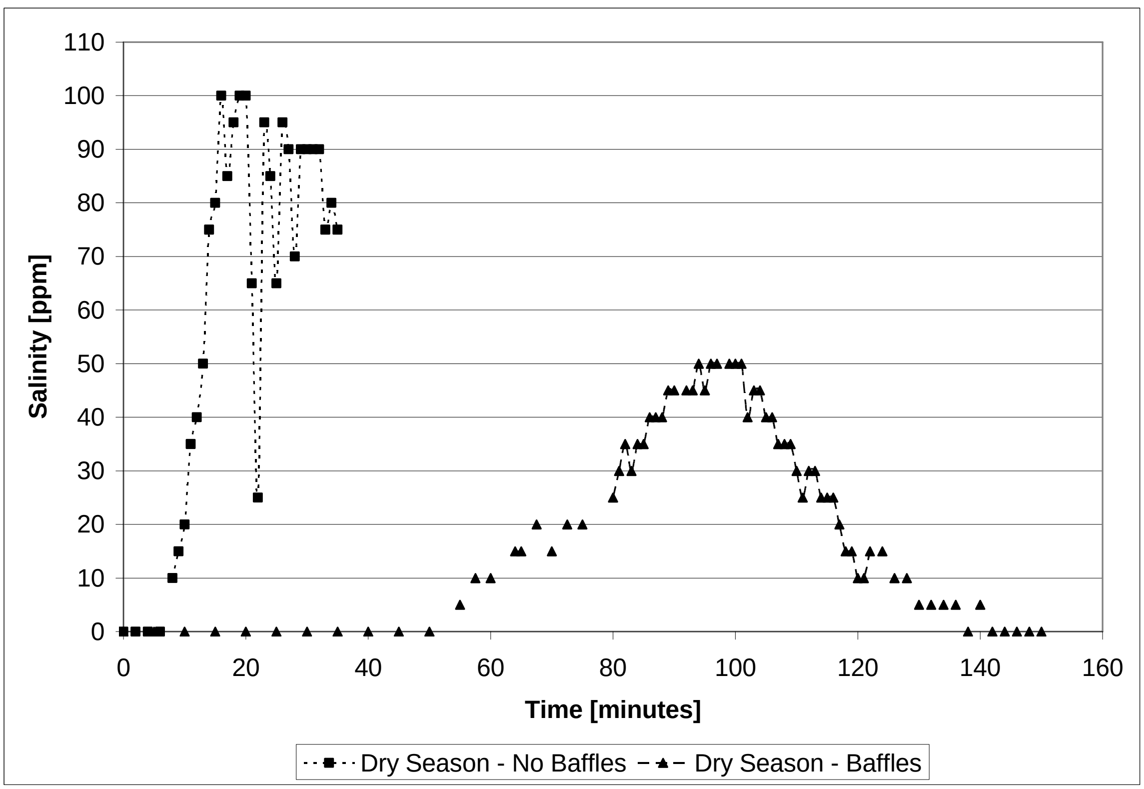


Figure 6-4: Dry season flow test results.
Time shown is for the tracer.

The tracer study can be further evaluated by calculating the mass of tracer that was recorded as passing out of the filter compared to the known mass put into the system. For the dry season tests, these data are summarized in Table 6-3. It makes sense that less tracer would be recorded at the water surface because of the density difference of the tracer.

Table 6-3: Tracer Test Mass Conservation

Test	**Mass In**	**Mass Out**	**% Measured**
Dry Season – No Baffles	440 g	210 g	48%
Dry Season – Baffles	500 g	220 g	44%

In conclusion, for these two flow tests under similar influent flow volume and water quality, the baffles increase residence time and produce a higher quality effluent. The turbidity in the first case was reduced 53% from 30 NTU to 14 NTU. After adding the baffles the reduction was 86% from 38 NTU to 6 NTU. Part of this improvement can be attributed to cleaning the gravel. The clean HFRF with baffles can achieve the treatment goals for SP-10 turbidity during the dry season.

6.3.3.2 Rainy Season Load

The order to better understand the performance of the HFRF during rainy season turbidity levels, which range from 200 to 400 NTU, high turbidity water was sent through the SP-10 HFRF. The water was agitated at the collection basin, raising the turbidity to between 100 and 500 NTU, or three to 15 times the dry season average turbidity of 30 to 40 NTU.

The HFRF removed over 90% of the turbidity over the duration of this test. Even still, because the influent turbidity was so high, effluent turbidity was 20 to 30 NTU. This is above the treatment goal of the HFRF. The SP-10 treatment processes, including the HFRF, could be modified so that even during the high turbidities of the rainy season the goal of water with 10 NTU or less can be met.

During this high turbidity test another tracer test was also conducted. It resulted in a tracer residence time of about 90 min. This result is similar to the result of the other test run after the baffles were installed.

6.3.4 Coefficient of Filtration for Spring 10 Filter

The filter coefficient relates filter performance to filter length, based on Fick's law and general filtration theory, as shown in Equation 6-2 (Wegelin et al., 1987; Ochieng and Otieno, 2006).

$$\frac{dc}{dx} = -\lambda c \qquad \text{Eq. 6-2}$$

In Eq. 6-2, c is a measurable water quality parameter, x is distance measured along the length of the filter, and λ is the filter coefficient in units of inverse length.

The filtration efficiency, E, is the ratio of effluent concentration, C_e, to influent concentration, C_o, and is related to the filter coefficient and the filter length, L, as shown in Equation 6-3.

$$E = \frac{C_e}{C_o} = e^{-\lambda L} \qquad \text{Eq. 6-3}$$

The total effluent quality can be found by finding the filtration efficiency for a series of filter media and their respective lengths. In the case of the Spring 10 Filter in MaeLa, this is not necessary as there is only one filter medium. Thus Equation 6-3 can be directly applied.

Ochieng and Otieno (2006) found that a filter coefficient calculated for an individual filter results in the most accurate theoretical filter efficiency. The variability of water quality and suspended particle load is unique to every influent, so the best calculation of the coefficient of filtration is from existing data. Equation 6-3 can be rearranged in order to find the filter coefficient based on filter efficiency, as shown in Equation 6-4.

$$\lambda = \frac{-1}{L}\ln\left(\frac{C_e}{C_o}\right) \qquad \text{Eq. 6-4}$$

As discussed in Chapter 5, the influent and effluent turbidities for the Spring 10 Filter were taken in three flow scenarios: dry season, clean filter; dry season, dirty filter; and wet season simulation, clean filter. Table 6-4 summarizes the Spring 10 Filter runs, influent and effluent turbidities, and respective filter coefficients, as calculated using Equation 6-4. The Dry season, Dirty filter scenario is based on the condition of the filter in January 2008, two months after the last cleaning in November 2007.

Table 6-4: Spring 10 Flow Scenarios and Filter Coefficients.

Flow Scenario	**C_o [NTU]**	**C_e [NTU]**	**λ [m^{-1}]**
Dry season, Clean filter	38	6	0.15
Dry season, Dirty filter	30	14	0.06
Wet season simulation, Clean filter	240	14	0.24

6.3.5 Extrapolation of Filter Coefficient

The three flow scenarios completed during the field work do not include a simulation of wet season turbidity levels when the filter is dirty. In order to predict filter efficiency in the Wet season, Dirty filter flow scenario, it is necessary to find the filter coefficient for this scenario. This can be done experimentally or through extrapolation of the coefficients found for the other flow scenarios at SP-10.

Since the source is the same year-round, the size of the suspended particles will not vary over the course of the year. Particles of the same physical dimensions and characteristics will settle at the same rate, especially with minimal annual viscosity variation which is the case in Thailand where the water temperature does not vary greatly. Thus the removal mechanism of the roughing filter, particle settling, will work at approximately the same rate throughout the year. Under this case, the ratio between wet and dry season filter coefficients is shown in Equation 6-5.

$$\frac{\lambda_{DrySeason,CleanFilter}}{\lambda_{DrySeason,DirtyFilter}} = \frac{\lambda_{WetSeason,CleanFilter}}{\lambda_{WetSeason,DirtyFilter}} \qquad \text{Eq. 6-5}$$

Based on this relationship, the Wet Season, Dirty Filter filter coefficient is 0.10.

$$\lambda_{WetSeason,DirtyFilter} = 0.10 \qquad \text{Eq. 6-6}$$

This calculation assumes that the mass of sediment in the filter during the Wet season, Dirty filter scenario is the same as the mass of sediment in the Dry season, Dirty filter scenario. The mass of sediment in the filter reduces the efficiency of the filter (Wegelin, 1996). As noted above, the Dry season, Dirty filter coefficient was calculated based on the filter operation two months after the latest cleaning. In the wet season, there will be even more sediment deposition in the filter, so the efficiency of the filter will be further reduced. The value of 0.10 may be a liberal estimate of the filter coefficient, but as discussed below this scenario hopefully will not occur.

6.3.6 Filter Length

Based on the Spring 10 Filter-specific filter coefficients summarized in Table 6-4, it is possible to predict performance of a horizontal-flow roughing filter design for Spring 10. If the existing filter is lengthened, or a second filter is built, filter performance will improve. Using Equation 6-3, the effluent concentrations given the filter coefficient and a new length can be predicted. Equation 6-7 shows the rearrangement of Equation 6-3.

$$C_e = C_o e^{-\lambda L} \qquad \text{Eq. 6-7}$$

Using this information, the effluent turbidity of the filter is predicted over a range of lengths for the four flow scenarios. The results are shown in Figure 6-5.

The existing filter is 12 meters in length. Only under the Dry Season, Clean Filter condition, an effluent turbidity of less than 10 NTU is achieved. Notably, when the filter length is 24 m all the flow scenarios except Wet Season, Dirty Filter, predict an effluent turbidity of less than 10 NTU. Not until the filter is 38 m long, more than three times the length of the existing filter, do all four flow conditions achieve below 10 NTU effluent values. The Wet Season, Dirty Filter coefficient is also a liberal estimate and so it could take an even longer filter to achieve the desired treatment.

Ideally the Wet Season, Dirty Filter flow condition would not occur. This means that a filter of double the existing length should achieve the desired effluent turbidity level during the remaining possible conditions. The main limitations on a long filter are construction and maintenance costs and land availability. At the site of the existing Spring 10 Filter, there is not enough land area to triple the filter length. There is enough space to double the filter size.

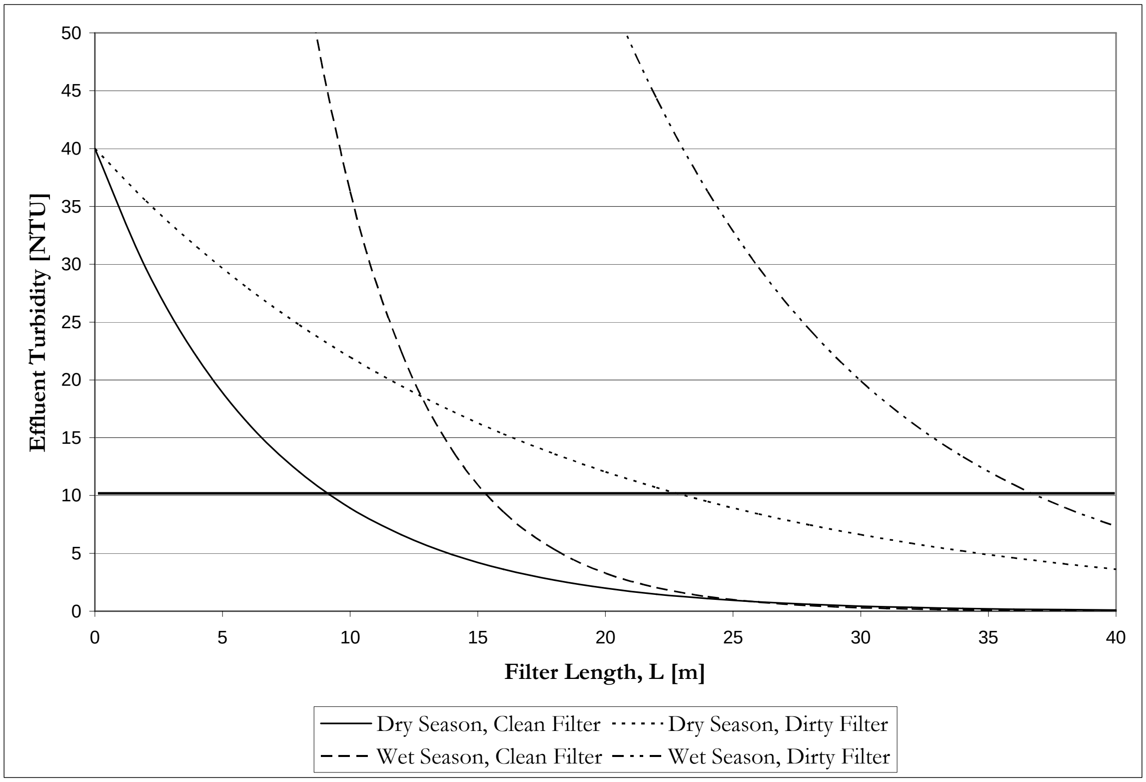


Figure 6-5: Effluent turbidity as a function of filter length and flow condition.

6.4 Microbial Sampling

Microbial sampling was completed at one place on each of the major distribution lines in the camp. This testing was done across the camp in order to determine the effectiveness of chlorination as a disinfection technique. The results of the testing are shown in Table 6-5, which reports the *E. coli* and total coliform counted.

These data, though sparse, are representative of the entire water system. Chlorination achieves disinfection in all the systems in which it is used. Notably, the water from SP-14 is not disinfected before reaching consumers.

In addition to sampling in the distribution system, the inflow and outflow of SP-10 HFRF were sampled. These *E. coli* and total coliform counts are shown in Table 6-6. These data show that the number of *E. coli* was reduced after filtration and that the number of total coliform increased after filtration. Since sampling only took place on one day, it is not possible to conclude either that the filter effectively removes *E. coli* or that the flow conditions in the filter allow total coliform to re-enter the filtrate. Instead these results should be considered as indicators of presence or absence of these organisms.

These positive counts demonstrate that there is microbial contamination in the SP-10 water prior to it reaching the SP-10 tank. At the tank chlorination takes place and SP-10 water is free from biological contamination when it reaches the tap, as shown in Table 6-5.

Table 6-5: Distribution System Microbial Sampling Results.
Reported in Colony Forming Units per 100-milliliter.

System	**Sample Location**	***E. coli* CFU 100-mL^{-1}**	**Total coliform CFU 100-mL^{-1}**	**Chlorinated [Y/N]**
A	Tap 7	< 100	< 100	Y
B	Tap 4	< 100	400	Y
C	Tank	< 100	< 100	Y
Christopher	Tank	< 100	< 100	Y
MOI	Tank	< 100	< 100	Y
SP-10	Tap 5	< 100	< 100	Y
SP-14	Tank	500	2700	N
SP-17	Tap 13	< 100	< 100	Y

Table 6-6: SP-10 HFRF Microbial Sampling Results.

Sample	***E. coli* CFU 100-mL^{-1}**	**Total coliform CFU 100-mL^{-1}**
HFRF Influent	200	3100
HFRF Effluent	< 100	5200

7 RECOMMENDATIONS

The purpose of this work is to improve MaeLa spring water quality by recommending treatment technologies that are easily implemented and operated. First, modifications, including maintenance, to the Spring 10 (SP-10) filter that will improve its performance are addressed. Second, the application of a general filter design for the other twelve springs is discussed.

7.1 SP-10 Filter Modifications

Information about the spring water quality and treatment was gained through the analysis of turbidity and flow volume from 2005, 2006, and 2007 and field study of the SP-10 horizontal-flow roughing filter (HFRF) The combination of an additional filter and improvements to the existing filter will meet the treatment demands of the system, particularly that which is a problem at present—high turbidity during the rainy season.

7.1.1 SP-10 Box A and VFRF

Based on the turbidity measurements taken along the water-collection structures of SP-10, both the VFRF rock filters preceding the HFRF were shown to be ineffective. Based on this information the VFRF was removed and the rocks in Box A were replaced with 2-4 cm gravel. The effectiveness of such a short, 1 m, HFRF in Box A is unknown, but the use of gravel instead of large rocks should at least reduce the velocity of flow through Box A, preventing re-suspension of solids from the bottom of the box.

7.1.2 Outflow collection chamber for existing filter

The existing HFRF filter has neither an inlet weir, an inflow distribution chamber, an outflow collection chamber, nor an outlet weir. Weirs are used in HFRFs for maintaining constant water volumes within the filter by only allowing inflow and outflow from above the top of the filter media. Chambers located at the inlet and outlet distribute and collect, respectively, the flow over the depth of the filter (Wegelin et al., 1991).

Since the saline tracer was not passive, it cannot be used to determine vertical distribution of flow at the inflow pipe. The tracer studies and baffle addition did show that there was horizontal short-circuiting in the filter which was corrected by the baffle installation. In order to determine the vertical distribution of flow at the inlet, a tracer study would need to be conducted and the concentration of tracer over depth at the outflow would need to be recorded. Since this test would be time consuming and could be expensive, the installation of a perforated pipe to distribute the flow vertically at the inlet is a comparable effort and expense and is recommended. The pipe should be of 3-inch or 4-inch diameter and perforated every 0.5 to 1-inch. It should be installed at the inflow of the filter where the influent water will flow into it. This is a simple improvement that will improve vertical distribution of the influent water.

The combination of an outflow collection chamber and an outlet pipe located at the top of the filter can be used to collect water over the depth of the filter and maintain a constant volumetric flow through the filter (Wegelin et al., 1991). The existing outlet pipe in the SP-10 filter is a vertical-slotted pipe with an outflow at the bottom of the filter. The upper half of the outflow pipe is shown in Figure 7-1. This construction does not hold a constant volume of water in the filter, allowing water to exit the filter more quickly than the theoretical residence time of the filter. In order to achieve maximum filter performance, water should remain in the filter for as close to the theoretical residence time as possible.

Figure 7-1: Slotted outlet pipe..

If, instead, the effluent water was collected at the top of the filter, then the flow velocity through the tank would be regulated and a constant volume of water would be held in the filter. This can be achieved by using an existing pipe located at the top of the filter and by collecting the water over the depth of the filter in a collection chamber. The construction of the chamber will require a slight reduction in the length of the filter, but will allow water to flow easily into the existing outflow pipe. To make the chamber, a slotted wall should be constructed 0.25 m away from the existing wall which contains the effluent pipes. The wall would be built with off-set concrete blocks in the same construction style as the internal walls of the filter. The new slotted wall is shown in Figure 7-2 in profile, plan, and cross-section view. Figure 7-2 only shows the third compartment of the filter.

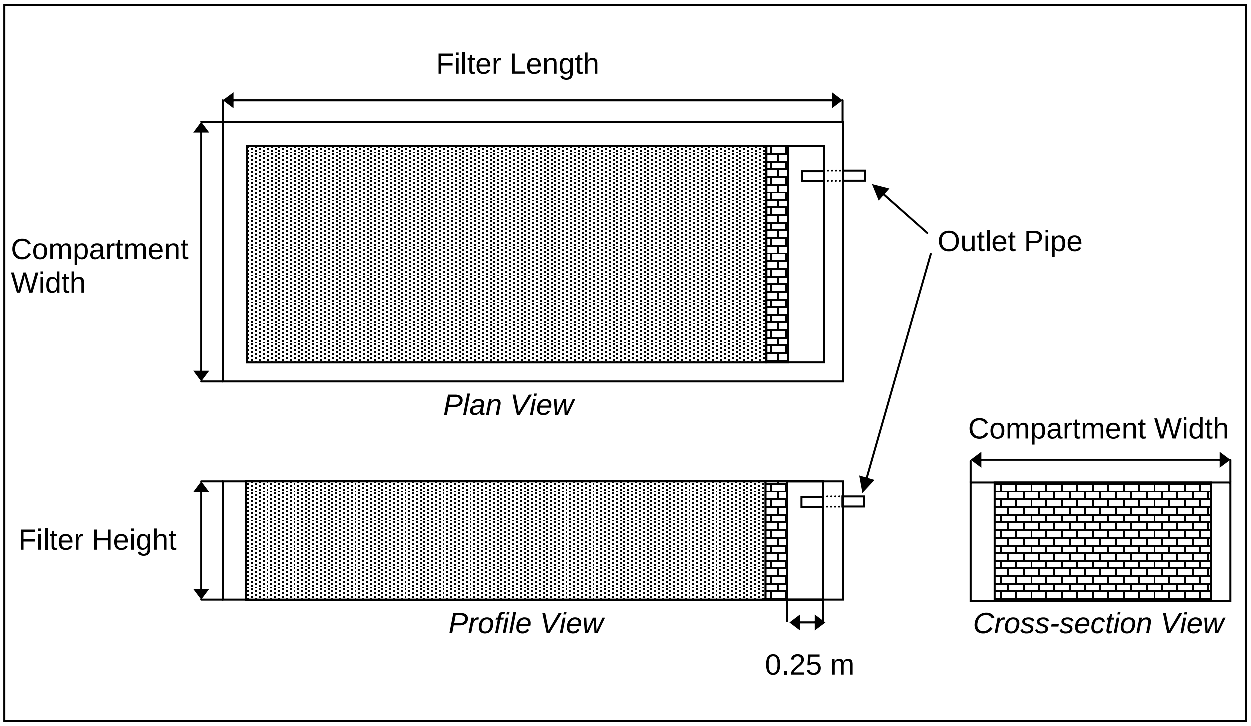


Figure 7-2: Design of outflow collection chamber.
Shown is the third compartment of the existing filter, with the collection chamber wall shown in horizontal brick fill and the filter media shown with dots.

The filter already has an outflow pipe near the top of the filter. This outflow pipe would need to be connected on the outside of the filter to the existing pipe which flows to the SP-10 ring tanks, as shown in Figure 7-3. The new pipe connection should be the same diameter as the existing outflow pipe so that there is no loss of head as the water enters the pipe to the SP-10 ring tanks.

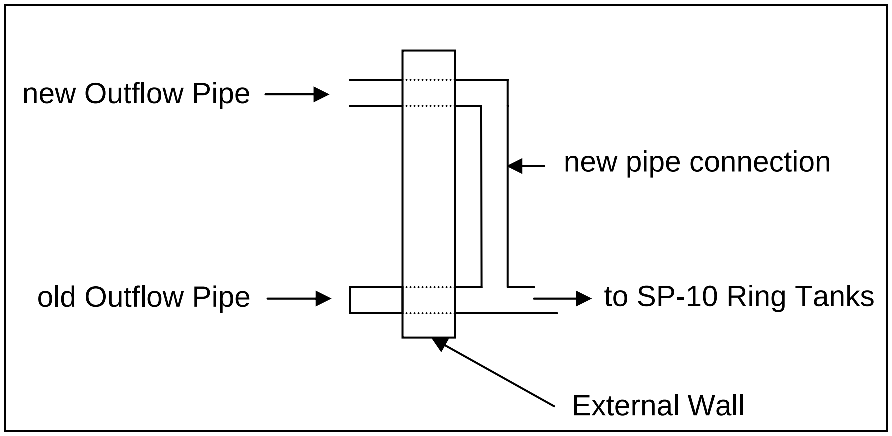


Figure 7-3: Design of outflow pipe at top of filter.
Profile view of the external wall of the filter and pipe connections.

7.1.3 Second equivalent filter

The second recommendation in order to meet the treatment goals of the system is to build a second filter at SP-10 which is equivalent to the first, including an outlet weir as described in Section 7.1.1. As shown in Chapter 6, according to the coefficient of filtration derived for each of the four flow scenarios, doubling the filter length to 24 m means the treatment goal of less than ten NTU in the effluent water is achieved in three of the four flow scenarios. The only flow scenario in which it is not achieved is the wet season, dirty filter scenario. Ideally this condition will not occur with proper filter maintenance described in Section 7.1.4.

Using three different-sized gravels in the three compartments of the existing HFRF was considered as an alternative to building a second filter. There are several problems with this alternative, though. First, the availability, size, material, and quality of smaller gravel are unknown. Second, in order to predict the effectiveness of a combined media filter, the filtration coefficients for each material need to be known. These coefficients can only be derived empirically through pilot- or full-scale testing with the water that will be treated. As the material and material filtration coefficients are unavailable, it is impossible to predict the efficiency of this alternative modification and it is not further considered. In addition, the operation and maintenance of the HFRF already installed at SP-10 is known by the staff and can be improved with minor modifications. The maintenance of a filter with smaller filter media would present further complications which could mean the treatment goals would not be met.

The second filter should be operated in parallel with the existing filter. This means the influent pipe should split and half the flow should travel to the first filter and the other half should travel to the second filter. A valve should be installed in each pipe just downstream of the point in the pipe where the flow is divided in order for all the flow to be diverted to one of the filters if necessary. The construction of outflow collection chambers in both of the filters will ensure that the flow entering either filter is treated for the same amount of time.

7.1.4 Maintenance

In order to keep the new and existing HFRFs operating so they meet the treatment goal, both filters need to be maintained. The first step to maintaining the filters is daily or weekly monitoring of influent and effluent turbidity levels in order to determine the efficiency of the filter. As discussed in Chapter 6 and particularly shown in Table 6-2, the measurement techniques currently employed by the AMI staff are not accurately measuring turbidity in the water. To collect useful turbidity information, a regularly calibrated electronic nephelometer should be used. The LaMotte turbidimeter currently owned by AMI would be effective if regularly calibrated. In addition the staff members that are using the turbidimeter should be trained to use it and collect accurate data.

Second, the filters will need to be cleaned when the effluent water quality is not meeting the treatment goals. In 2007 the filter was cleaned in July, August, and November. As seen in Table 7-1, the effluent turbidity fell from June to July and from November to December as a result of cleaning. A benefit of the two parallel filters is that one filter can easily be taken off-line for cleaning by closing the valve in the inflow pipe. In addition, during lower volumes of flow during the dry season, it may be possible to only operate one of the filters, thus reducing the labor demand of cleaning the filters. Another benefit of having two filters is that the total amount of solids collected will be distributed over two filters instead of one, thus theoretically increasing the amount of time between cleanings.

Currently the filters are cleaned manually. Mechanical cleaning of HFRF is an option which would reduce the need for labor and reduce the amount of time the filter is offline. In order to effectively remove solids from the filter, turbulent flows of 0.5-1.5 meters per minute are needed. Wegelin (1996) writes the ideal flushing flow would be 1.0-1.5 m min^{-1}. Taking 1.0 m min^{-1} as the flushing flow goal, the volume of water that needs to be flushed is 18 m^3 min^{-1}.

Currently there is one three-inch drain pipe in each of the three compartments. The drainage velocity out of these pipes is related to the height of water in the filter, h, and gravity, g, as shown in Equation 7-1.

$$v_p = \sqrt{2gh} \qquad \text{Eq. 7-1}$$

The water will flow through these pipes at 4 m s^{-1}. From the flush rate and the velocity of water through the drainage pipes, the area of pipes needed can be found. The area needed is five times the present area, so five three-inch pipes need to be added to each compartment. With six three-inch drainage pipes per compartment, the flushing velocity of 1.0 m min^{-1} is achieved. The amount of time it will take for the filter to drain under these conditions is 45 seconds.

Figure 7-4 shows the equidistant placement of the six drainage pipes along the bottom of the filter. In addition, a perforated three-inch collection pipe is shown on the inside of the filter. In order to assure that the filter medium does not interfere with the high flow rate, this perforated collection pipe will create a volume with no restriction to flow. The collection pipe should be directly connected to each of the six drainage pipes.

The form of Equation 7-1 assumes that the height of water in the filter remains constant over the flushing. Since the flushing volume is the same as the volume of the filter, 15 m^3, it will be necessary to replace this volume at the same rate at which water exits the filter in order to maintain the same head over the duration of flushing. First, this means that this volume of water must be available. AMI was planning on constructing storage tanks for this purpose along the SP-10 collection pipeline, at the location of the VFRF. Second, this volume of water must be able to reach the HFRF at the same rate that water is being flushed out.

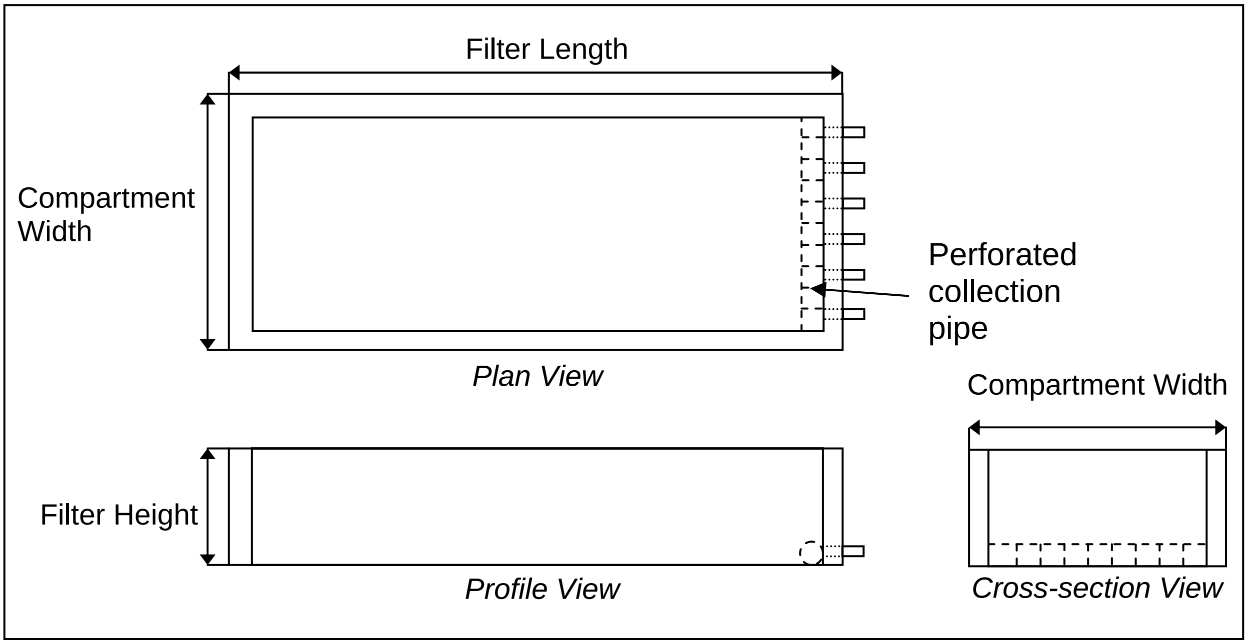


Figure 7-4: Design of drain pipes for filter maintenance
Shown is one of the three compartments of the existing filter. All three compartments should be modified in the same way. The six three-inch drainage pipes are shown, as well as the perforated collection pipe.

In order to achieve this flow rate the head in these tanks needs to be maintained as well so that Equation 7-1 is still applicable. This requires storing two times the necessary volume or 30 m^3. This can be achieved in 12 eight-ring tanks made with one-meter diameter rings. The ring tanks should be constructed in two rows of six. Six of the tanks will have two three-inch pipes which connect to the HFRF. The other six tanks, placed behind the first row, will each have two three-inch pipes which connect to one tank in the first row.

This flushing system is a significant investment of capital. It will require the addition of twelve ring tanks and the pipes necessary to connect the tanks to the HFRF. If AMI chooses to construct this system, I recommend they make the pipe connections between the storage tanks and the HFRF temporary. This will require that the pipes are reconnected for each flushing, but this should only be one day in every two to four months. During the months they are not in use they can be locked at A Tank or the MaeLa 2 Office. Detaching these pipes will require labor to set up on the day of the flushing, but since the flushing will take less than one minute, the entire process should only require the services of day laborers for one day. This is in contrast to the current manual medium regeneration method which requires five days of labor. It should be reiterated that manual medium regeneration is an effective means of cleaning the HFRF and is as recommendable as mechanical regeneration.

7.2 General filter design

One purpose of this work was to provide a general filter design that can be constructed at the twelve springs currently without filters. Review of the turbidity levels collected weekly in 2007 shows than no spring other than SP-10 has elevated turbidity throughout the rainy season. The data are available in Table 3-1.

The springs which had a monthly average turbidity over 10 NTU are SP-2, SP-8, and SP-10. SP-2 and SP-8 had only one month with an average exceedance, while SP-10 exceeded 10 NTU every month. In addition to these springs, SP-7 and SP-12 each had at least one weekly exceedance of 10 NTU, but these did not result in monthly averages more than 10 NTU. Since only SP-10 has consistently elevated turbidity, it is not recommendable to construct a roughing filter at any of the other twelve springs.

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