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Effective water treatment for rural communities in Suriname : a comparison of point-of-use ceramic filters and centralized treatment with sand filters

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EFFECTIVE WATER TREATMENT FOR RURAL COMMUNITIES IN SURINAME: A COMPARISON OF POINT-OF-USE CERAMIC FILTERS AND CENTRALIZED TREATMENT WITH SAND FILTERS

By

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A REPORT

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This report, "Effective Water Treatment for Rural Communities in Suriname: A comparison of point-of-use ceramic filters and centralized treatment with sand filters" is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN ENVIRONMENTAL ENGINEERING.

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ABSTRACT

For countless communities around the world, acquiring access to safe drinking water is a daily challenge which many organizations endeavor to meet. The villages in the interior of Suriname have been the focus of many improved drinking water projects as most communities are without year-round access. Unfortunately, as many as 75% of the systems in Suriname fail within several years of implementation. These communities, scattered along the rivers and throughout the jungle, lack many of the resources required to sustain a centralized water treatment system. However, the centralized system in the village of Bendekonde on the Upper Suriname River has been operational for over 10 years and is often touted by other communities. The Bendekonde system is praised even though the technology does not differ significantly from other failed systems. Many of the water systems that fail in the interior fail due to a lack of resources available to the community to maintain the system. Typically, the more complex a system becomes, so does the demand for additional resources. Alternatives to centralized systems include technologies such as point-of-use water filters, which can greatly reduce the necessity for outside resources. In particular, ceramic point-of-use water filters offer a technology that can be reasonably managed in a low resource setting such as that in the interior of Suriname. This report investigates the appropriateness and effectiveness of ceramic filters constructed with local Suriname clay and compares the treatment effectiveness to that of the Bendekonde system. Results of this study showed that functional filters could be produced from Surinamese clay and that they were more effective, in a controlled laboratory setting, than the field performance of the Bendekonde system for removing total coliform. However, the Bendekonde system was more successful at removing *E. coli*. In a life-cycle assessment, ceramic water filters manufactured in Suriname and used in homes for a lifespan of 2 years were shown to have lower cumulative energy demand, as well as lower global warming potential than a centralized system similar to that used in Bendekonde.

1.0 INTRODUCTION

Insufficient access to safe drinking water is a challenge the world over. According to the UN in 2006, over one billion people lack sufficient access to safe drinking water (UNDP 2006). Many agencies grapple with these inadequacies and strive to help families and communities meet their daily water needs. There have been innumerable water-treatment technologies and aid projects implemented over the last several decades, in a wide variety of settings. Most of these projects have been well intentioned but unfortunately have not always been successful. In a report to USAID in 1981, it was recorded that as much as 35-50% of improved water and sanitation systems in developing countries became inoperable within 5 years of installation (Elmendorf 1981). More recently, data gathered from 20 different African countries revealed that a high percentage of hand pumps (a technology known to be relatively sturdy and easily maintained) were no longer "functional"; 13 countries reported that more than 30% of hand pumps were nonfunctional, and 3 countries reported as many as 60% were broken (Committee 2010).

In Suriname, a country with vast disparities between urban and rural communities, organizations and communities face similar development challenges. There have been countless projects and technologies implemented to help rural communities meet their drinking water needs. Many of these projects have built centralized treatment and distribution systems to be able to utilize the abundant surface water available in many areas of the country. However, in a 2009 survey of 28 rural villages by UNICEF, only 4 out of 16 water treatment systems were operating. Lack of resources and sense of ownership on behalf of the communities have been cited as reasons for failure (Smith 2011; IDB 2007). Successful, long-term operation, on the other hand, has occurred for a centralized water treatment system installed in the village of Bendekonde. The system in Bendekonde has been operating uninterrupted for nearly 10 years, a duration that far exceeds any other systems in the interior of Suriname. However, this system operates largely due to the diligence of a handful of dedicated volunteers, and it is foreseeable that it too could eventually be added to the list of nonfunctional systems were they to no longer donate their time, or a major repair is needed.

Point-of-use treatment solutions offer an alternative to centralized systems are as they can be administered in individual family homes. In particular, ceramic water filters are a simple technology that, in most settings, can be created using readily available materials: clay, rice husks, and water. Ceramic water filters have been ranked highest for appropriateness when compared with other small-scale water-treatment options in low resource settings such as those found in the remote interior of Suriname (Partnership 2010). Whereas the system in Bendekonde relies on the efforts of several individuals to supply an entire community with clean drinking water, ceramic water filters require that individuals and families personally take action towards meeting their needs, thus improving the likelihood of sustainability of the system.

This report will evaluate characteristics of local Surinamese clay to determine the appropriateness of its use for producing ceramic filters. This report will also compare the treatment effectiveness of ceramic filters made from Surinamese clay to that of the Bendekonde centralized water treatment system.

2.0 STUDY OBJECTIVES

This study is intended to serve as a resource for baseline information regarding ceramic water filter production for interior communities in Suriname, and to provide a comparison to previously implemented technologies. For the purposes of exploring fundamental capabilities of local filters, colloidal silver was excluded from any filters manufactured for this study. While research shows that colloidal silver consistently improves the treatment effectiveness of the filters, it has been also shown that acceptable treatment levels can been achieved without its inclusion (Lantagne 2001; Oyanedel-Craver 2008). Part of the goal of this research is to investigate treatment technologies that are manageable by interior communities without dependence on outside aid. The addition of colloidal silver could contradict this goal as it is only available outside of Suriname's borders, whereas all other materials to produce filters are readily available in most regions in the country. This research was conducted with the assumption that were filters to be produced in Suriname, there would be the knowledge that, if resources allowed, colloidal silver could be included to further enhance their treatment effectiveness

There are three primary objectives for this study:

1. To assess physical properties of Surinamese clay and investigate applications of the clay to the production of ceramic water filters.
2. To compare the treatment effectiveness of the Bendekonde water system to that of ceramic filters made from Surinamese clay by measuring each technology's ability to remove harmful bacteria (*E. coli* and total coliform).
3. To provide information for communities, NGO's, and other organizations working to improve drinking water for interior communities in Suriname in order to aid in their decision making processes and planning while also aiming to lessen communities' dependence on outside aid.

3.0 BACKGROUND

3.1 Suriname and Saramacca

Suriname is a country located on the north-eastern shore of South America, north of Brazil and east of French Guiana (see Figure 1). Most of the country is relatively uninhabited, dense, tropical rainforest. The vast majority of the population resides in the northern, more developed coastal region of the country, while the minority of the population carves out an existence in remote interior villages. Of the ten districts in Suriname (shown in Figure 1), Paramaribo and Wanica districts represent 0.4% of the total land area, yet 70% of the population live within their boundaries(UNICEF 2001). On the other hand, Sipaliwini comprises 80% of the country's land area and is inhabited by less than 10% of the population.

Figure 1: Suriname map. Figure shows the study area, the Upper Suriname River. (www.mapsof.net)

Suriname is a former Dutch colony. Its history is deeply rooted in plantations and the slaves who were brought from the African continent to work their fields. As the colony was first being formed and settlements established in the 17th century, the slaves were initially brought by the Atlantic Slave Trade, with slaves originating from West Africa. The treatment of the slaves by plantation owners had a reputation of being among the worst in the region (Postma 1997). With the assistance of the Amerindians, natives of South America, many slaves escaped into the surrounding rainforest and began to establish new communities and forge a very unique society. After decades of escapes and raids on the plantations, slavery was officially abolished in Suriname in 1863. However, the plantations still relied heavily on large numbers of cheap manual laborers. In order to maintain production and profits, indentured servants were brought from the United Kingdom, Indonesia, and India for the decades that followed (Hoefte 1998). As the dynamics in the capital city and the surrounding plantations continued to change, the escaped African slaves remained relatively untouched in the Surinamese rainforests.

When the African slaves, typically referred to in Suriname as Maroons in reference to their dark skin color, escaped into the jungles, they formed several tribes. The two primary remaining tribes are the Saramaccan and the Aucan. This report's study area is within a region considered part of traditional Saramaccan territory along the upper reaches of the Suriname River (see Figure 1). The Saramaccans developed communities along the Suriname River as far as 200 miles from the capital city of Paramaribo, with the intention being to isolate and protect themselves from the plantations and plantation owners. They cleared land for planting, hunted and fished for meat, and built their homes in the forest. After the abolition of slavery in 1863, many these of the communities maintained their way of life and have remained considerably isolated from the coast and capital for the last 150 years. Their villages are mainly only accessible by boat or small airplane. An aerial view of a village on the Upper Suriname River near the study site is shown in Figure 2. Figure 3 shows an example of characteristic housing in a Saramaccan community. With the exception of utilizing corrugated-steel roofing in place of the traditional palm fronds, little has changed in the style and construction of their homes over the past 300 years. The remoteness of the communities has done much to preserve their culture, but it has also limited the availability of many resources and basic services.

Figure 2: Aerial view of a Saramaccan village on the Upper Suriname River

Figure 3: Characteristic housing in a Saramaccan community.

3.2 Development and Water in the Interior

There are great disparities between the coastal region and the interior in regards to access to basic services such as education, healthcare, electricity, sanitation, and safe drinking water. For example, in a 2001 report by UNICEF, only 20% of the people living in the interior were reported as having access to safe drinking water, as compared to the 92.6% reported in the coastal capital. Sanitation statistics are similar; 30% of people in the interior have access to improved sanitation (primarily latrines), while 98% of people in the capital have access to sanitation systems for sewage and solid waste (UNICEF 2001).

Figure 4: Hygiene in Saramaccan communities. Men and women bathe, do laundry, and wash dishes in the river.

There are roughly 80,000-100,000 people living in the interior of Suriname (UNICEF 2001). Without access to safe drinking water, many rely primarily on untreated surface water to meet their daily needs. Most Saramaccan communities are located along the Upper Suriname River, which serves not only as the primary avenue of transportation but is also the location where nearly all washing (clothes, dishes, body) is done. Unfortunately, many people lacking access to sanitation facilities will also defecate directly into the river. If a creek is near the community, it is typically the source used for drinking water. Figure 4 shows a washing area in the Suriname River. Figure 5 provides an example of a path women often travel to collect water for their families. During the dry seasons the water levels in the creeks will often get very low, or go completely dry, decreasing the water quality and availability and forcing community members to seek other sources. Some homes utilize rainwater catchment systems, but these systems are rarely adequate to meet the household's needs throughout the dry season (see Figure 6). Some families and individuals will seek to treat their drinking water in some way (boiling or filtration), but it is not a widespread practice.

Figure 5: Water collection in Saramaccan communities. Women following a path to a creek near the village to retrieve drinking water.

Figure 6: Example of a rainwater catchment system in a Saramaccan community.

Suriname has two dry seasons: August to November and February through April. The longer dry season (Aug-Nov) often poses the greatest health risks to community members due to the decreasing water quality in creeks and limited rainfall. By comparing data on incidences of diarrhea with precipitation amounts, one can observe the trend of increased incidences during periods of minimal rainfall. See Figure 7 below. The incidences of diarrhea were recorded and provided by a private, non-profit, primary health care organization, Medische Zending (MZ). The numbers are reported in cases per 100 registered residents. More information about MZ and the seasonal health trends on the Upper Suriname River can be found in a report by the author located in Appendix A.

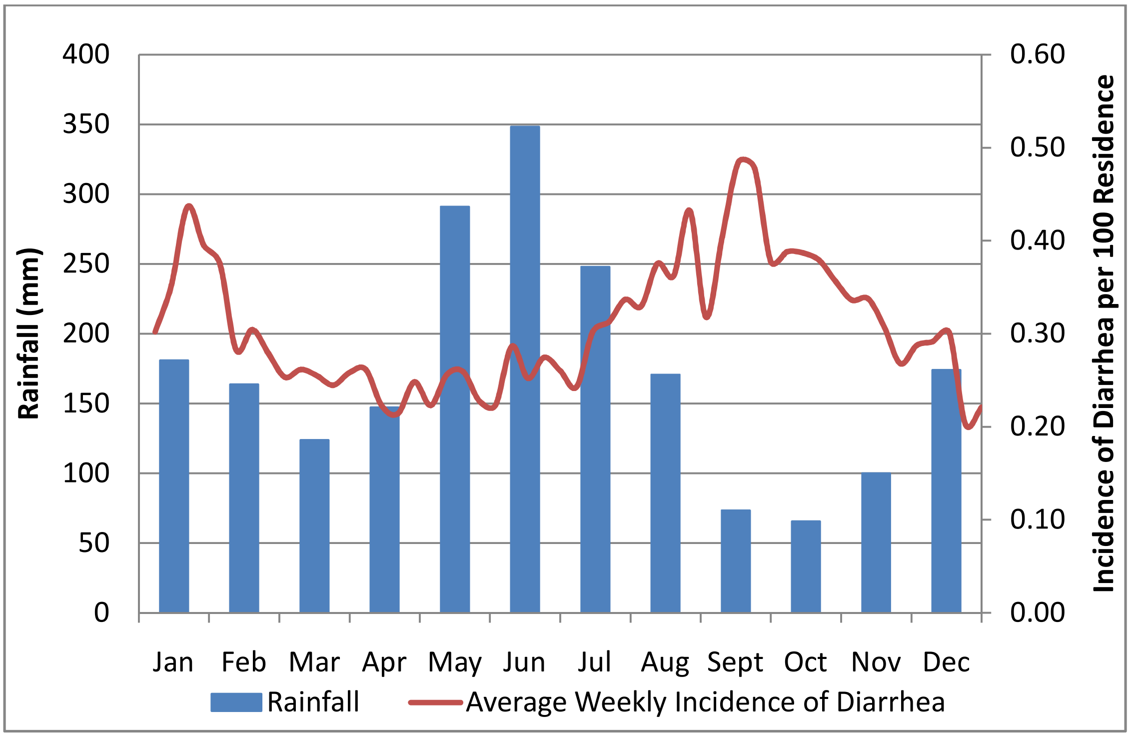


Figure 7: Average weekly incidence of Diarrhea on the Upper Suriname River (2000-2009) and average monthly rainfall at Dramhoso (1961-1968). Dramhoso is located in the Sipaliwini District roughly 30-40 miles north of the southern reach of the Upper Suriname River. Incidences of diarrhea were recorded by Medische Zending (medischezending.sr) and are reported per 100 residents.

To address these health concerns, there have been many water-related projects implemented along the Upper Suriname River by various agencies, such as Rotary International, and Dutch NGOs. While some villages have been equipped with water treatment systems, few of the systems are operating, and only a few of those operating seem to be treating water successfully. In 2009, UNICEF Suriname surveyed 28 villages throughout the interior and found that 16 of the villages were equipped with centralized water treatment and distribution systems, but only 4 of those systems were operating properly. In the villages surveyed, 75% of the implemented water systems were no longer operational.

There are many reasons for projects failing, and it can be difficult to pinpoint the primary reason, or even several reasons (Smith 2011). There have been studies in Suriname to examine the causes of failure, one of which was done by the International Development Bank (IDB). In a document released in 2008, the IDB stated:

"As for the interior of Suriname, limited participation from the communities and the sustainability of the investments in terms of technical capability and adequate Operation and Maintenance (O&M) remain key areas to be addressed to improve water supply."

Involvement of the community in the project process and the resources available to the community to maintain the system once installed are areas in need of improvement in Suriname's efforts to improve access to safe drinking water in the interior. Based on the track record of centralized treatment systems in the interior of Suriname, one could argue that the communities resembling those on the Upper Suriname River do not have sufficient access to the resources required to maintain and/or manage centralized treatment and distribution systems. Smith studied the sustainability of three community managed water systems on the Upper Suriname River in 2011. Two communities were reported as not having sufficient funds for maintenance or repairs, and the third had refused to contribute towards the maintenance of the system (Smith 2011). Due to inadequacies in project implementation and/or available resources, all three systems were failing to meet the World Health Organization's (WHO) guidelines for providing access to improved water.

3.3 Bendekonde Water System

Despite challenges and failed water systems along the Upper Suriname River, there is one village-managed system that stands out as a success. The water system in the village of Bendekonde has been operating without major interruption since 2001. Bendekonde has a population of roughly 200 people and is approximately 170 miles from Paramaribo (120 miles by road, and an additional 50 miles by river boat). People from other communities on the Upper Suriname River will often reference the Bendekonde system when discussing water treatment options for their own villages as a desired solution. Based on informal interviews by the author with community members, there seems to be the general perception that the Bendekonde system technology is superior to others and that is the reason for the longevity of operation.

Figure 8: Bendekonde Water Treatment System

The system was originally installed along with several others (with identical technologies) along the Suriname River by a group known as the Community Development Fund for Suriname (CDFS) in 1999, but all of them broke down within a year or two of operation. The Bendekonde system was then retrofitted by *Gemeente Amsterdam Waterleidingbedrijf* (GAW), Amsterdam Municipal Water Works. The current system treats river water using a three step-process: first the water is screened by a rapid sand filtration system, second the water undergoes microbial treatment through a slow-sand filter and associated *schmutzdecke* layer (the bio-film layer providing biological treatment), and finally the water receives ultraviolet (UV) disinfection. The updates by GAW included: replacing the original pump installed by CDFS which had broken, supplying solar panels for powering the system instead of the diesel operated generator, building structures to house the storage tanks and filters, replacing the polyethylene tank used for the rapid-sand filter with a stainless steel tank, and providing the equipment to perform UV disinfection. The entire system is solar powered; lessening the community's operating expenses. A schematic of the system is shown in Figure 9. There are roughly 11 taps and/or wash stations distributed throughout the village which are shared by the households nearby (shown in Figure 10). General maintenance requires monthly scraping of the *schmutzdecke* layer to increase flow rates through the slow-sand filter, annually removing and washing all the sand from the slow-sand filter, backwashing the rapid-sand filter, bi-monthly chlorination of the distribution network, and any other repairs as needed.

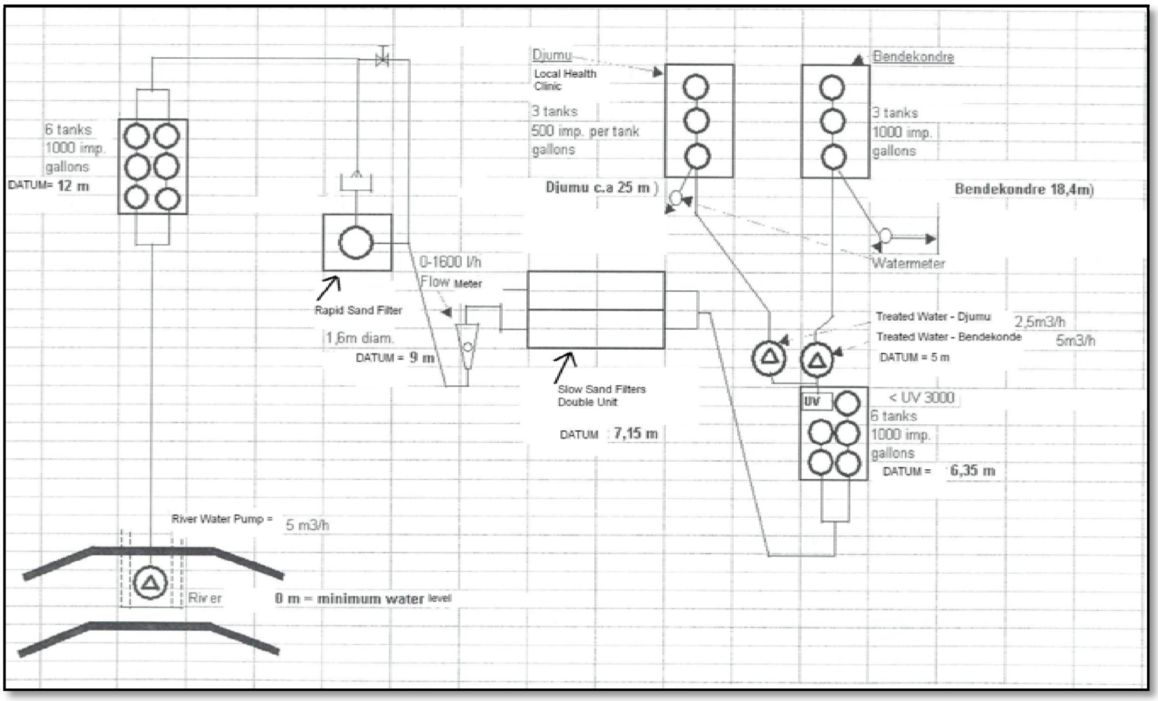


Figure 9: Bendekonde water system schematic

Figure 10: Bendekonde wash station

The management and maintenance responsibilities of the system are shared by the local women's organization and a man named Ile Pansa. All labor involved in the management of the system is on a volunteer basis; no one is paid for their efforts. Mr. Pansa monitors the system daily and individually performs all maintenance to the system himself with the exception of the annual washing of the sand, which he organizes into a community event with the expectation that all able-bodied members in the community will participate. The women's group has assigned one woman from the community to keep the system free of weeds and overgrowth from the surrounding jungle. There is a monthly fee assessed per household of $3.00 SRD (roughly $1.00 USD). The fee is intended to be collected and saved for future repairs as needed but is rarely paid, and minimal amounts had been saved as of 2011 (Ile Pansa, personal communication).

Even with the upgrades and modifications by GAW, the Bendekonde system is relatively similar to other USR community systems and technologies. The village of Masiakiki (roughly 15 miles downriver from Bendekonde) has a water treatment system installed by CDFS in 2005 that, similar to Bendekonde, was equipped with a river intake pump, solar panels, and a slow-sand filtration system. The Masiakiki system operated successfully until 2009 when the pump broke. Despite numerous efforts by community members and Peace Corps volunteers in the area, as of 2012, the pump had yet to be fixed and the system was falling into disrepair. The villages of Semoisie (5 miles downriver from Bendekonde), and Malobi (20 miles downriver from Bendekonde) have the same system as that installed in Masiakiki, and both are no longer operating.

Currently, the Bendekonde system is one of the few water systems operating successfully in the interior of Suriname. After examining the management and operations of the system, however, it becomes evident that the system is not markedly different from other installed systems, and is operating due to the diligence of a handful of volunteers, and possibly a bit of luck. Much of the community is relatively uninvolved in the operation, and is understandably unaware of the demands or intricacies of the system. Were those currently maintaining the system to no longer donate their time and efforts, or there was a major repair needed for which there are limited funds, the system could easily slip into disrepair or cease to operate. When considering sustainable and appropriate technologies for water treatment on the USR, it is not clear that the system in Bendekonde is the best option.

3.4 Ceramic Water Filters

Ceramic point-of-use (POU) water filters employ a straightforward technology that has proven to be an effective low-cost water treatment solution in Central America, Asia, and Africa (Group 2011). In their most basic form, ceramic filters are easily constructed by mixing and forming three very simple materials: clay, water, and some sort of flammable material (sawdust, rice husks, or even flour). When the filters are fired in a kiln at controlled temperatures (reaching maximum temperatures of 800-900° C), the flammable material burns out while the clay particles sinter together, creating very small pores throughout the ceramic body that act as a physical screen, filtering out harmful bacteria. Laboratory tests have shown ceramic filters are capable of removing up to 90-99.5% total coliforms, and 97.86-99.97% of *Escherichia coli* (Lantagne 2001; Oyanedel-Craver 2008). Treatment effectiveness has been further enhanced (100% removal of total coliforms and *E. coli*) with the addition of colloidal silver to the filter body, applied by either painting or submerging the filter after firing (Lantagne 2001). Investigations of the field performance of the filters have consistently shown a reasonable improvement in public health through the reduction in incidents of diarrheal disease (Lantagne 2001; Clasen et al 2005; Brown 2006). However, the study by Clasen et al (2005) in Colombia found that while the filter may be treating water successfully, the overall living conditions and hygiene practices of community members plays an important role in the intervention's ability to reduce incidences of diarrheal disease. Education should always be an integral aspect to implementation.

Potters for Peace (PFP, pottersforpeace.org), a non-profit organization based in Arizona, has done much to disseminate information regarding the technology, and the production of filters. Through their efforts, filter factories have been started in at least 10 countries around the globe (Group 2011). The PFP filter design is shaped similar to a ceramic flower pot (a cylindrical shape with a flat bottom), and when in use, is suspended inside a receptacle (ceramic or plastic) and equipped with a spigot. See Figure 11 for PFP filter and receptacle. The filter can typically hold about 8 L of water depending on dimensions, and PFP recommends flow rates of 1-2 liters per hour. Faster flow rates are thought to be indicative of preferential flow paths (e.g., cracks) that allow water to pass untreated and slower rates are thought to be impractical (Kaira Wagoner, personal communication). Flow rate is often the only recommended measure of quality before filter distribution in many of the production factories without supplies or resources for water quality testing (Group 2011).

Figure 11: Potters for Peace ceramic water filter with plastic receptacle

Ceramic filters provide a low cost water treatment solution that can be produced with local materials, and has shown to be a viable option for many communities around the world. In a recent booklet (Smart Disinfection Solutions), the PFP filter scored highest for appropriateness when ranked against other small scale water treatment options (Partnership 2010). The simplicity in the design and fabrication of ceramic filters, and readily accessible materials, make them a very attractive option for communities with limited access to resources, such as the communities along the USR. Whereas the centralized treatment system in Bendekonde is being maintained by a small group of volunteers, in the case of ceramic point-of-use filters, the actions of one or two individuals will not supply the community with clean drinking water. Individuals and families would be required to personally take action towards providing themselves with clean drinking water.

3.5 Participatory Strategy

In an attempt to improve project success rates, many development organizations around the world have begun to consider, or are already utilizing, participatory strategies. As part of the author's Peace Corps service, she had the opportunity to work with UNICEF as a member of their Water, Sanitation, and Hygiene (WASH) team. At the time, UNICEF Suriname was undertaking a pilot program in the interior aiming to maximize participation of the communities involved while addressing WASH challenges. One definition describes *participation* as "involvement by local populations in the creation, content, and conduct of a program or policy designed to change their lives"(Jennings 2000). These types of strategies have been adopted by development organizations in HIV awareness programs, for improving hygiene practices, and providing a guiding framework for discussions about sanitation facilities. Central to the "participatory" philosophy is the dedication not to do for others what they can do for themselves. The goals are to find ways to engage community members in development discussions, provide a catalyst to action, and ultimately to form strong, equal partnerships between donors and beneficiaries.

Participatory approach methodologies differ from conventional development strategies which are typically donor driven as opposed to community driven. Instead of forming partnerships with communities and working collectively to develop priorities and plans of action, conventional development projects, in the their extreme, involve donors arriving with funding in-hand for a pre-determined project, and dictating to the community what will be done. Unsurprisingly, conventional approaches do little to foster pride or a sense of ownership on behalf of the community members, and thus are prone to perpetuate a cycle of dependency on outside aid.

While certain studies have heralded the benefits and successes of participatory approach strategies, some field workers remain cautious (Michener 1998; Jennings 2000). Field workers have called into question the integrity of participatory approach strategies and point out the many challenges involved in achieving true and genuine participation when dealing with communities who may "see participation as an opportunity to extract resources from a willing agency" (Michener 1998). Within development work there will always remain difficulties in communication and struggles to find common ground between donors and beneficiaries. However, regardless of the rhetoric used in describing a project, it is obvious that by gaining the buy-in of community members, one is ensuring more long-term commitment on their behalf, and thus improving the sustainability of the intended outcomes.

UNICEF employed a combination of two pre-existing methodologies for their WASH program: Participatory Hygiene and Sanitation Transformation (PHAST), and the Community Life Competence Process (CLCP). The PHAST methodology mainly utilizes illustrations as a means to stimulate conversations between people and provide opportunities for information sharing, with the goal being to link health status with sanitation practices, and to empower community members to take action. CLCP centers on the philosophy that all communities of people, regardless of location, age, gender, or type of community, are able to collectively define a dream and/or goal and take action towards achieving it. The CLCP process provides suggested activities to encourage discussion and, most importantly, action. Whereas PHAST targets WASH types of challenges, CLCP allows the community not only to participate in the development of the solution, but also in the definition of the perceived problem. By infusing the two methods, UNICEF hoped to engage community members in all stages of the development process, while also providing some guiding framework with the addition of PHAST.[1]

4.0 METHODS

The methods section is divided into sub-sections describing the various stages involved in this research: material preparation of the clay and rice husks, physical properties testing, ceramic disk fabrication, kiln operations, hydraulic conductivity testing, coliform and *E. coli* analyses, analysis of the Bendekonde treatment effectiveness, and ascertaining the ceramic disk treatment effectiveness. In 2011 PFP led a collective effort to produce a working manual, "Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment", compiling existing knowledge on the various stages of filter production, and to

[1] Information obtained from an internal manual produced by, and shared between, UNICEF Suriname and The Constellation. "WASH Integrated Methods: Facilitators' Manual". March 2011.

“Provide guidance to assist filter factories in producing the most effective ceramic filters at the lowest cost” (Group 2011). Information provided in this manual was used to formulate many of the methodologies used for this report and in creating ceramic water filters.

4.1 Material Preparation for Testing and Ceramic Fabrication

The materials used for the production of the ceramic water filters in this study were clay, rice husks, and water. Clay from Suriname was acquired via a local ceramicist (Soeki Irodikromo) working in Paramaribo. Mr. Irodikromo has an agreement with a bauxite mine in the Commewijne District, which is a coastal district near the eastern border (Figure 1) and receives regular deliveries of clay extracted from approximately 10-meters deep. Mr. Irodikromo processes the clay by drying and then sieving to remove impurities before using it for his ceramic artwork. When dried, the clay sample acquired for this study weighed approximately 30lbs. Due to this fairly limited supply of Surinamese clay, additional clay from a landslide near Ontonagon, MI (46.7°N, 89.2°W) was also collected to act as a trial sample in the development of the methodologies and as well as to provide a comparison for the results of the Suriname clay. Both clay samples were completely air dried before being crushed by a hammer-mill, creating a fine powder. The pulverized clay was then sieved through a U.S. Standard No. 30 sieve, and the portions passing the sieve were retained for use in testing and fabrication. The portions of the clay not passing the No. 30 sieve were then re-processed in the hammer-mill, and sieved again. Approximately 40-lbs of crushed and sieved rice husks were obtained from Rice Hull Specialty Products, Inc (Stuttgart, Arkansas). The rice husks were the remainders of a sample that passed a No. 30 sieve but was retained on U.S. Standard No. 80 sieve, ensuring both large and small particles were removed from the sample. As a result of the material preparation, the clay and rice husks were able to be mixed together by hand in dry powder form before adding water. Figure 12 shows a sample of clay and rice husk in dry form prior to mixing.

Figure 12: Prepared Ontonagon clay (darker material) and rice husk (lighter-colored material) prior to mixing.

4.2 Clay and Mixtures Properties Testing

Basic geotechnical properties of several mixtures with varying rice-husk-to-clay ratios were evaluated for the Suriname and Ontonagon clays. Both clays were tested for plasticity, shrinkage, and porosity *without* rice husks, and with 10% and 20% rice husks by dry weight. In addition, a mixture of Ontonagon clay with 15% rice husks by dry weight was prepared for testing. Due to the limited supply of Suriname clay, the 15% mixture was not prepared or tested. In total, seven mixtures were tested and compared. The tests were performed in order to evaluate the Suriname clay for its use in ceramic water filter fabrication, and to compare the Suriname results with those from a different clay, in this case a local Michigan source. The following section will describe the methods used for the three tests: water of plasticity, shrinkage, and porosity. All three tests are recommended by PFP in establishing baseline information for a new clay source, and the methods described here are referenced from their manual (Group 2011).

Water of plasticity tests were performed to understand the workability and the water content required to reach a workable state for the two clay sources and the various rice husk/clay mixtures. To determine the water plasticity, a 500g sample of dry sieved clay (see Material Preparation) was weighed in a stainless steel bowl. If it was a clay/rice husks mixture, it then was hand mixed with rice husks (either 10%, 15% or 20% by weight). Water was then slowly added in small increments (10-20 mL) and mixed thoroughly between each addition. This process was continued until the sample reached a consistency appropriate for molding. Determining the consistency appropriate for modeling is subjective as it is based on appearance and feel. For the purposes of this study, water was added to the sample until it was cohesive, held its shape, and did not crack when pressed. If the sample became sticky, it was considered to have passed the desired consistency, and it was kneaded to allow for drying to the desired consistency. Once the desired consistency was reached, the amount of water added was recorded and the water plasticity was calculated using Equation 1. PFP reports that water plasticity can range from 10% to 30% for highly plastic clays (Group 2011).

$$\%\,\boldsymbol{Water\ of\ Plasticity} = \frac{\boldsymbol{Mass\ of\ Water}}{\boldsymbol{Mass\ of\ Dry\ Clay}} \times \mathbf{100}\% \qquad \textbf{(1)}$$

Shrinkage of the two clay types and various mixtures was assessed after firing in a kiln. After completing the plasticity tests, the prepared samples were used to construct 4 bars, 14 cm by 4 cm and 1-cm thick, from each mixture. The top of each bar was marked with a 10-cm long groove. When the samples were sufficiently air dried, and showed no visible signs of moisture, the bars were fired in a kiln reaching a maximum temperature of 800°C. To prevent cracking of the bars, the temperature in the kiln was closely monitored and gradually increased over a period of 10.5 hours for the Ontonagon bars, and 11 hours for the Suriname bars. See the Kiln Operations section for more information. After the kiln and bars had cooled sufficiently to remove the bars, the grooves were measured to determine the total linear shrinkage. To calculate the total linear shrinkage, Equation 2 was used, where the plastic length was 10 cm.

Six filter factories in Burma report an average shrinkage of 10-14% for clay, and 5-6% for clay/rice husk mixtures (Group 2011).

$$\% \boldsymbol{Total\ Shrinkage} = \frac{\boldsymbol{Plastic\ Length - Fired\ Length}}{\boldsymbol{Plastic\ Length}} \times \mathbf{100}\% \quad \textbf{(2)}$$

Porosity of the samples was determined by first measuring the water absorption using the same bars from the shrinkage test. Porosity is critical to the filtration rates and treatment effectiveness of ceramic water filters. While the bars from the shrinkage tests were still warm from the kiln, they were first weighed dry and then placed in boiling water. Steam from the boiling water condensed in the pores, forcing air out and saturating the pores. After five minutes, the bars were removed from the water, the surface dried with a damp sponge, and the saturated weight of the bars was determined. To calculate the water absorption Equation 3 was used.

$$\% \boldsymbol{Absorption} = \frac{\boldsymbol{Saturated\ Mass - Dry\ Mass}}{\boldsymbol{Dry\ Mass}} \times \mathbf{100}\% \quad \textbf{(3)}$$

Then, Equation 4 was used to determine the porosity of the ceramics. The specific gravity of the solids in the ceramic body was assumed to be 2.65, a typical value for clays (Coduto 1999).

$$\% \, Absorbtion = w = M_w / M_s \quad (4a)$$

$$n = \frac{V_v}{V_s} \quad (4b)$$

$$\frac{\mathbf{1}}{\boldsymbol{n}} = \mathbf{1} + \frac{\mathbf{1}}{\boldsymbol{SG_S * w}} \quad \textbf{(4c)}$$

where M_w = mass of water (g)
M_s = mass of solids filter (g)
V_V = volume of voids (cm^2)
V_s= volume of solids (cm^2)
n = porosity
SG_s = specific gravity of solids (in reference to water)

4.3 Disk Fabrication

Because only a limited amount of clay from Suriname was available for this study, disks were fabricated to act as representative samples of larger filters. Disks were made with dimensions according to the PFP recommendations for typical filter thicknesses (1-3 cm).

Mixtures of 10% and 20% by dry weight rice husk were prepared for both clay types. Clay and rice husks were first hand mixed in their dry form for 2-3 minutes to ensure uniform distribution of the materials. The water quantity related to the plasticity (determined previously) for the given mixture ratio was added to the dry mix in increments of 20-30 mL, mixing thoroughly between each addition. The quantities of materials for the four mixtures prepared are listed in Table 1.

Table 1: Material Quantities for Disk Fabrication

Location – Rice Husk/Clay % by Weight	Clay (grams)	Rice Husk (grams)	Water (mL)
Ontonagon – 10/90	700	83	267
Ontonagon – 20/80	750	175	315
Suriname – 10/90	700	83	274
Suriname – 20/80	750	175	306

Three disks were constructed for each of the four mixtures, for 12 disks in total. The completely blended mixtures of clay, rice husks, and water were divided into three equal samples, later to become disks. The three individual samples were then kneaded to remove any remaining air bubbles and clumps. A PVC-mold and hydraulic press were utilized to form the disks. The prepared samples were centered in a PVC-ring with an inner-diameter of 10.16 cm and placed on the bottom platen of the hydraulic press. A PVC-cap with an outer-diameter of 9.84 cm was placed on top of the sample, and the sample was pressed at a pressure of 100 psi. The exerted pressure forced some of the clay sample to extrude through the narrow gap between the PVC cap and the PVC ring. The extruded clay was trimmed and discarded, while the disk sample remaining in the ring was removed. See Figure 13 for images of the disk pressing process.

Figure 13: Example of disk fabrication: (a) Top Left, Suriname clay and rice husk mixture prior to 100psi pressure being applied, and (b) Top Right, after applied pressure with extruded clay visible. (c & d) Bottom, disk removal from the PCV-ring.

Disks were then air dried for 10 days before being fired in a kiln to a maximum temperature of 800°C (see Kiln Operations section, below, for more details). After the disks were cooled, the circumferences of the disks were ground to a uniform diameter of 8.9 cm, to later be glued snuggly into PVC columns for testing. Due to the varying composition of the two clay types, each of the four mixtures yielded a different disk thickness, despite having similar quantities of clay and rice husks in the mixtures. Final disk dimensions are listed in Table 2.

Table 2: Kiln Fired Disk Dimensions and Mass. Disk diameters were all 8.9 cm.

Disks - % Rice Husk by weight		t (cm)	Mass (g)
	a	2.3	178.1
Ont -10%	b	2.3	180.5
	c	2.3	181.0
	a	2.4	159.0
Ont -20%	b	2.4	165.6
	c	2.5	162.4
	a	2.0	213.1
Sur -10%	b	2.1	205.0
	c	2.0	205.0
	a	2.3	187.6
Sur -20%	b	2.5	192.1
	c	2.5	190.5

4.4 Kiln Operations

Clay samples in this study were fired in a Lucifer high temperature muffle furnace (Warrington, PA) with temperature increases and heating durations performed according to the Ceramic Manufacturing Working Group recommendations (Group 2011). During the firing process the samples passed through several stages. This section will describe the general firing stages, and will review the procedures followed in this study.

PFP recommends firing ceramic filters to a maximum temperature of 700-900°C. When heated from room temperature to the recommended temperature, the filters will pass through six stages. The first stage occurs between 100-120°C and is referred to as "water smoking". During water smoking, the water remaining in the samples will vaporize and exit the pores in the form of steam. This phase is prone to cause cracking in the filters if the temperature increases too quickly, so PFP suggests allowing up to 4 hrs for the kiln to reach 120°C. Next, between 120-350°C, any vegetable matter remaining in the clay will decompose. The decomposition phase poses minimal risk of cracking, and the temperature can be increased at a rate of 100°C per hour. Between 350-450°C great care must be taken as this is the temperature at which the rice-husks will combust and if the temperature is not monitored closely there is a risk of cracking the filters. PFP recommends allowing 2 hrs for the kiln to rise from 350°C to 450°C; however, the combustion of the rice husk creates additional heat and the temperature can be difficult to control. Throughout this phase it is important to not only monitor the temperature inside the kiln, but also be sure to provide sufficient ventilation as the combusting materials will produce a fair amount of smoke. Once the combustion of the rice husks is complete, and there is no longer smoke emitting from the kiln, the temperature can be increased at a rate of 100°C per hour until it reaches 700°C. From 450°-700°C the clay becomes ceramic as the chemically bound water leaves the filters and the clay particles begin to sinter together. Finally, between 700°-900°C, the carbon in the filters will burn out. At this final temperature range, it is important for there to be sufficient oxygen present for the carbon to burn completely, and it is recommended to maintain between 800°-900°C for 1-3 hours. After firing is complete, the kiln and filters should be allowed to cool slowly before removing.

Figure 14: Ontonagon clay bars prior to firing. The grooves on the bars on the right are all 10-cm long. The bars are resting on firebricks in the kiln.

The furnace used for this study was located beneath a ventilation hood that, when the furnace door was cracked open, provided adequate air movement for the smoke and steam emanating from the heated filters to escape the furnace. To monitor the temperature inside the furnace, a thermocouple was used and the sensor was placed just above the samples. Figure 14 shows samples of Ontonagon clay (formed into bars for properties testing) positioned in the furnace prior to firing. The furnace is designed to reach a maximum temperature of 1,200 °C and does not allow for much precision at lower temperatures. Therefore, the temperature inside the furnace was difficult to control until it reached over 200 °C. Controlling the temperature was also difficult while the rice husks were combusting.

In total there were three separate firings: the first two firings were the Ontonagon and Suriname clay bars used for the shrinkage and porosity tests (each set of bars from their respective source were fired separately), and the third was both the Ontonagon and Suriname disks fired together. There were no samples damaged by cracking in any of the firings. During the firing of the Ontonagon and Suriname disks, the thermocouple was not reading accurate temperatures for the first 4-5 hours due to a low battery. Smoke did not begin emanating from the furnace (indicating the combustion of the rice husks) until the thermocouple read nearly 500°C, thus indicating to the author that the readings were inaccurate. Another thermocouple was acquired and the correct readings were taken from then on, and the readings from the first 4-5 hours were reduced by 25% for the kiln log. Fortunately, the error resulted in a more gradual increase of temperature and there was no damage to the disks. Kiln logs were kept for all firings and are shown in Figure 15. Also shown in Figure 15 are the PFP recommendations for firing duration and temperature increases, along with the six stages the clay samples underwent.

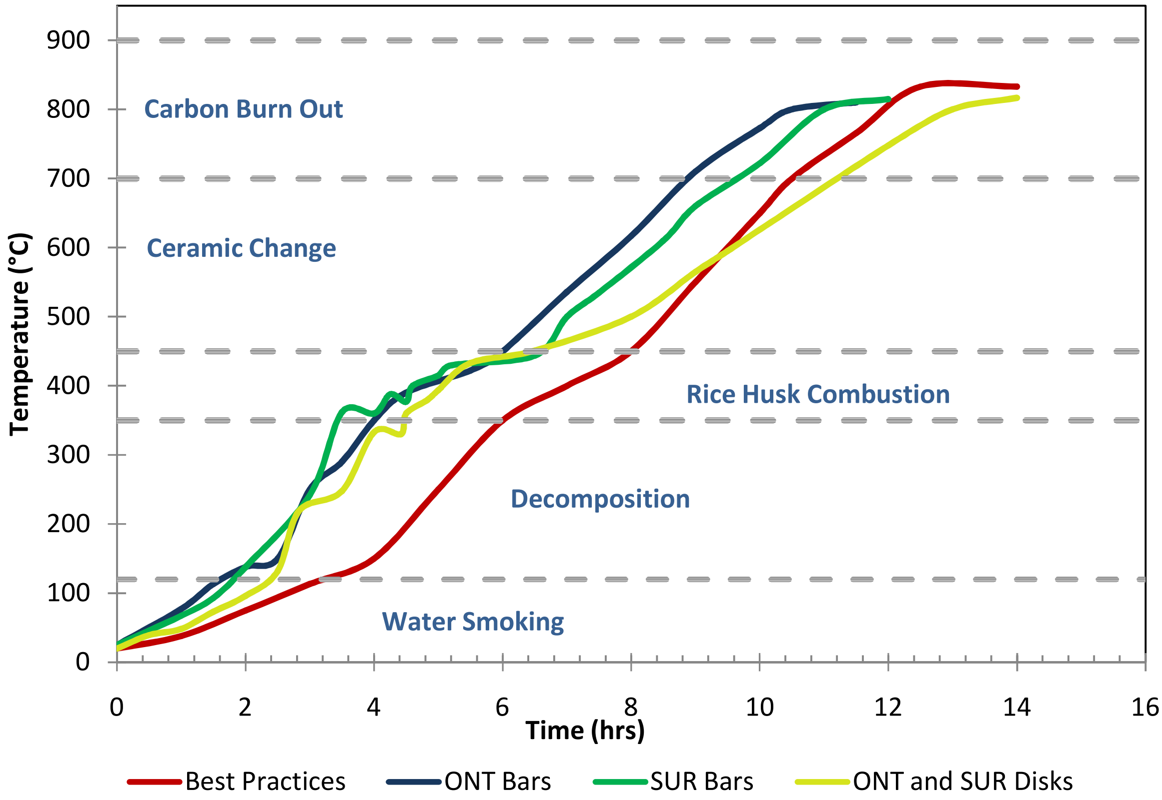


Figure 15: Kiln logs and ceramic stages. "Best practices" are those recommended in the Potters for Peace manual (Group 2011).

4.5 Hydraulic Conductivity

The hydraulic conductivity of the ceramic disks was determined through a series of a falling-head permeameter tests (Fetter 2001) with distilled water. The disks were placed inside a PVC coupling with an inner diameter of 8.9 cm (same diameter as the disks). The interfaces between the PVC coupling and the circumference of the disks were sealed to be water tight with silicone glue, and an 8.9-cm outer- diameter PVC pipe was secured inside the coupling, above the disk, using all-purpose cement. See Figure 16 for schematic of the disk assembly with the PVC pipes and fittings.

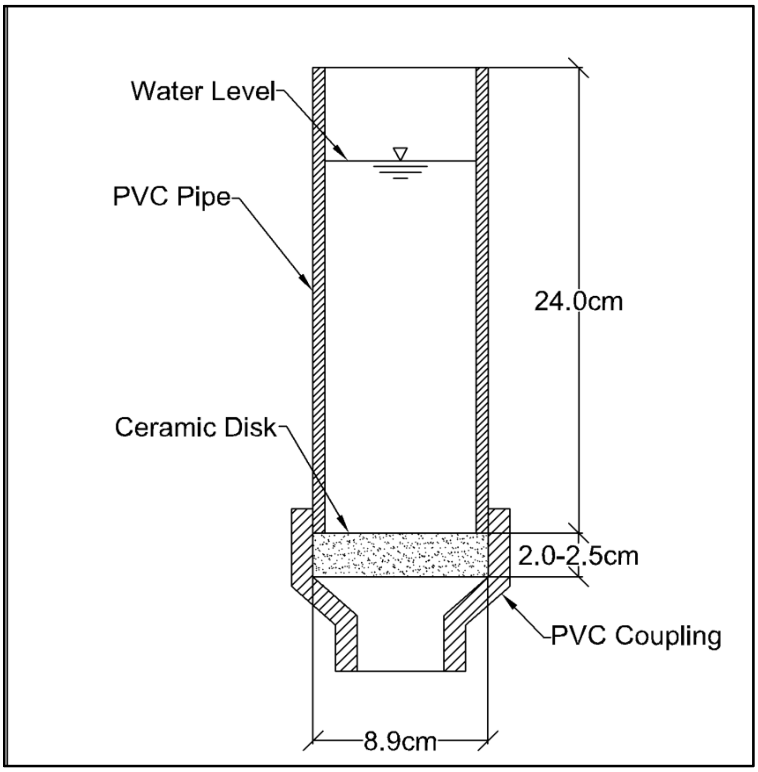


Figure 16: Disk and PVC coupling assembly. Left, cross-section view showing the ceramic disk, placed in the PVC coupling, with PVC pipe installed above. Right, actual PVC coupling and pipe installed in the lab.

Distilled water was used for the hydraulic conductivity test for two reasons: first, for initial testing the author did not want turbid water to slow down the flow rates through the disks, and, second, the residual effect of chlorine in tap water would have potentially interfered with later microbiological testing. To accurately simulate the hydraulic conductivity of fully operational filters, the disks were first soaked in distilled water for 12 hours prior to beginning the flow tests. Distilled water was then poured into the PVC pipes above the disks to a height of 24 cm, the average depth of pot filters reported by PFP (Group 2011), creating a volume of water of 1.49 L. The height of the water was monitored over time and, from the graphical representation of height as a function of time, the hydraulic conductivity of the disks was determined using Darcy's Law and Equation 5.

$$\boldsymbol{h(t) = h_0 \, e^{-\left(\frac{k}{b}\right)t}} \qquad (5)$$

where h = height of water at time t (cm)
h_0 = initial water height (24 cm)
k = hydraulic conductivity (cm/s)
b = disk thickness (cm)
t = time (s)

Once the hydraulic conductivity was determined, the expected flow through a full-sized filter could be calculated from a derivation from a previous study. The derivation of Darcy's Law by Van Halem for calculating flow through a PFP filter is provided as Equation 6. For the remainder of this study one complete volume of water (1.49 L) through the disks will be referred to as one "flush". Each disk was monitored for three to five flushes of distilled water. Two of the disks were found to be leaking when the flow tests were begun (ONT-20-c, and SUR-10-b). Due to the difficulty of removing the sealed and glued PVC fittings, these disks were discarded for the remainder of the study.

$$Q_{wall} = \frac{k}{b}\, 2\pi\left(\frac{r_1 - r_2}{6L}\, h^3 + \frac{1}{2} r_2 h^2\right) \tag{6a}$$

$$Q_{base} = \frac{k}{b}\, \pi (r_2)^2 h \tag{6b}$$

$$\boldsymbol{Q_{filter} = Q_{wall} + Q_{base}} \tag{6c}$$

where Q_{wall} = flow through the walls of the filter (mL/s)
Q_{base} = flow through the base of the filter (mL/s)
Q_{filter} = flow through the entire filter (mL/s)
r_1 = filter radius at water level (cm)*
r_2 = filter radius at base (cm)
L = length of the filter wall from the water level to the filter base (cm)

*Note: Example, if the filter is half full, the r_1 value is 15.5 cm.

4.6 Coliform and *E. coli* Analyses

For this study 3M Petrifilm™ *E. coli*/Coliform (EC) Count Plates were utilized to determine concentrations of *E. coli* and coliform present in the water samples. The EC plates are prepared with nutrients that react with beta-glucuronidase (produced by 97% of *E. coli*) to form a blue precipitate visible to the naked eye. The plates also contain a pH indicator that becomes visible (forms a red dot) when it comes in contact with acid produced by coliform bacteria during metabolic fermentation. A film affixed to the top of the plate traps gas formed from both the *E. coli* and coliform reactions, and the bubbles associated with either the blue or red colonies indicate the presence of *E. coli* and/or coliform, respectively. The plates are required to be incubated at 35°C for 24 hours in order for the reactions to progress sufficiently for the colonies to become visible. To ensure safe microbial quality of drinking water, the World Health Organization guidelines require that zero *E. coli* be present in the water sample (WHO 2008).

4.7 Bendekonde Treatment Effectiveness

The treatment effectiveness of the Bendekonde water system was evaluated by the ability of the system to remove pathogens (coliforms are an indicator of fecal contamination and, hence, the potential for the presence of pathogens) from the source water, namely the Suriname River. Water samples were collected and tested from three locations: the untreated source, after the rapid-sand filtration process, and from a community tap (after the slow-sand filtration and UV-disinfection process). Water was collected using plastic bottles previously containing purified water for drinking. The bottles ranged in size from 1.0 to 1.5 liters. In collecting water from the river, the cap was removed and the bottle was completely submerged underwater (near the intake pump for the system) until it was completely filled with water. The water was poured out and the process was repeated two more times. The third volume of water collected was not discarded, but was sealed with the cap and saved for testing. Collecting water after the rapid-sand filtration process required collecting the water from the drip system leading to the slow sand filters (see Figure 17). Similar to the river water collection process, the bottle was filled to capacity three times, discarding the first two volumes, and saving the third for testing. Of the 11 community taps (for example, Figure 10) in the distribution network, the tap closest to the distribution tanks was used for this study. When collecting water from the tap, the tap was opened and water allowed to flow for 1-2 minutes before beginning to fill the sample bottles. The same procedures followed while filling the sample bottles with river water and after the rapid-sand filtration water were followed for collecting water from the community tap.

Figure 17: Inlet to slow sand filter (Bendekonde)

As mentioned in a previous section, Bendekonde is a very remote community with limited access to electricity, making proper incubation very difficult to achieve. There was no incubator available or electricity to operate one. Therefore the plates were incubated utilizing human body temperature, which is naturally around 37°C. The plates were positioned between two pieces of cardboard (which acted as an insulator) secured with a rubber band, and then placed securely in the waistband of the water sampler for 24hrs. This method creates some variability in the incubation as it depends on the ambient temperature, as well as the ability of the sampler to maintain constant contact with the cardboard Petrifilm™ package for the full 24 hours while conducting normal daily activities. In a recent study assessing different methods of microbiological testing in the field, the method of using Petrifilm™ EC count plates and body incubation was listed as “not ideal” in a low-resource setting; however none of the enumeration methods assessed were determined to be “suitable” for such a setting, and many were deemed “not suitable” at all (Bain et al 2012). For the purposes of this study and the constraints of working in the field with limited suitable supplies, the variability was considered acceptable.

A single set of samples (from the three locations) was first collected in the middle of May 2011. Four more sets of samples were collected during the month of September 2011.

4.8 Ceramic Disk Treatment Effectiveness

As with the Bendekonde system, the treatment effectiveness of the ceramic disks was assessed by measuring their ability to remove bacteria, *E. coli* and total coliform. Contaminated water was obtained by diluting untreated waste water to 0.5-1.0% concentration in distilled water and thoroughly mixing. The untreated wastewater was acquired from the wastewater sewers on Michigan Technological University’s campus via a pumping and valve system located on the ground floor of the DOW Environmental Science and Engineering Building. The mixture ratios were designed to match the contamination levels seen in the Suriname River near Bendekonde which in 2011 were observed to be between 1-10 cfu/ml and 75-160 cfu/ml for E. coli and total coliform, respectively (see Figure 25 in Results section). Mixing was accomplished by combining the wastewater and distilled water in a container in increments of 4 equal volumes from each of their respective volumes. Between each addition, the container was shaken vigorously for 1-2 min.

The contaminated water mixture was then poured into the disk and PVC assembly (shown in Figure 16) to a depth of 22-cm. After three hours, 1 mL aliquots were taken from the tops of columns (to determine the influent concentrations), and from the receptacles (graduated cylinders) below the outlet of the PCV coupling (to determine effluent concentrations). Samples were inoculated with Petrifilm™ EC Count Plates and incubated at a temperature of 35°C for 24 hours. The fluctuations in waste water concentrations, and the variability of waste water contamination levels itself, resulted in influent contamination levels that ranged during various cycles from 3-21 cfu/mL for *E. coli*, and 6-50 cfu/mL for total coliform. The influent contamination levels during any one cycle were relatively consistent. After sampling was completed, the water remaining in the column was discarded, and the receptacles were sterilized by heating them to 170°C for two hours. This process of adding freshly mixed wastewater, and sampling after three hours, was considered one *cycle* of testing and will be referred to as such throughout the remainder of this report. To observe possible changes in flow rates, water levels were monitored for the three hours between the time after the contaminated water cycle started and before testing took place.

5.0 Results

The first test performed was to determine the amount of water required to achieve a plastic, workable consistency for the various clay/rice husk mixtures. The results from the plasticity tests are shown in Table 3. According to the guidelines stated by the Ceramic Manufacturing Working Group, all the Ontonagon and Suriname clay/rice husk mixtures rank within the highly plastic range of 30% or more water for plasticity (Group 2011). As expected, the addition of rice husks to the clay mixtures increased the amount of water required to reach a plastic state. These results were used to determine the amount of water to be added to the mixtures for disk construction.

Table 3: Water for Plasticity Results

Mixture - % Rice Husk (by weight)	Water for Plasticity (dry weight basis)
ONT - 0%	34.4%
ONT - 10%	34.6%
ONT-15%	36.6%
ONT-20%	43.2%
SUR - 0%	32.4%
SUR - 10%	36.2%
SUR 20%	41.0%

Figure 18 illustrates the results for the average total shrinkage of the clay/rice husk mixtures. With the exception of the Ontonagon 10% mixture, the addition of rice husks reduced the total shrinkage for both clay types. On average, the Suriname clay experienced more shrinkage. Reducing shrinkage is desirable because when manufacturing full-sized ceramic water filters, high amounts of shrinkage can cause warping and cracking.

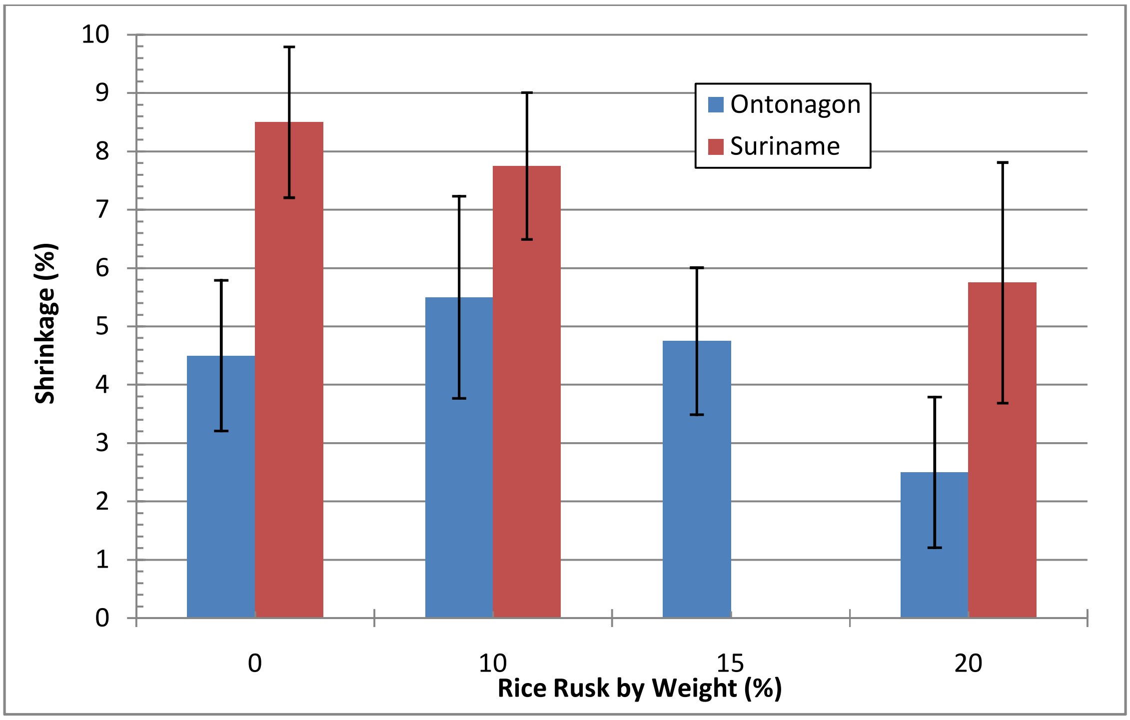


Figure 18: Total average shrinkage (n=4). Calculated from the measured change in length (after kiln firing) of the grooves on the tops of the bars. The error bars represent the standard deviation for the 4 ceramic bars tested from each mixture.

The porosity results are shown in Figure 19. The Ontonagon clay had higher porosity values than the Suriname clay mixtures by 10-15%. Suriname mixtures ranged from 16-37% porosity, and Ontonagon mixtures ranged from 29-47%. The porosity of ceramic filters has been reported to range from 30-44% (Halem 2006; Oyanedel-Craver 2008). However, prior to hydraulic conductivity and treatment effectiveness testing, it is not entirely possible to estimate if the porosity values observed here are within a desirable range or not. If the porosity is too high, it could result in compromised treatment capabilities, and if it is too low, the mixture may produce unfeasibly slow flow rates in order to supply a family with daily drinking water.

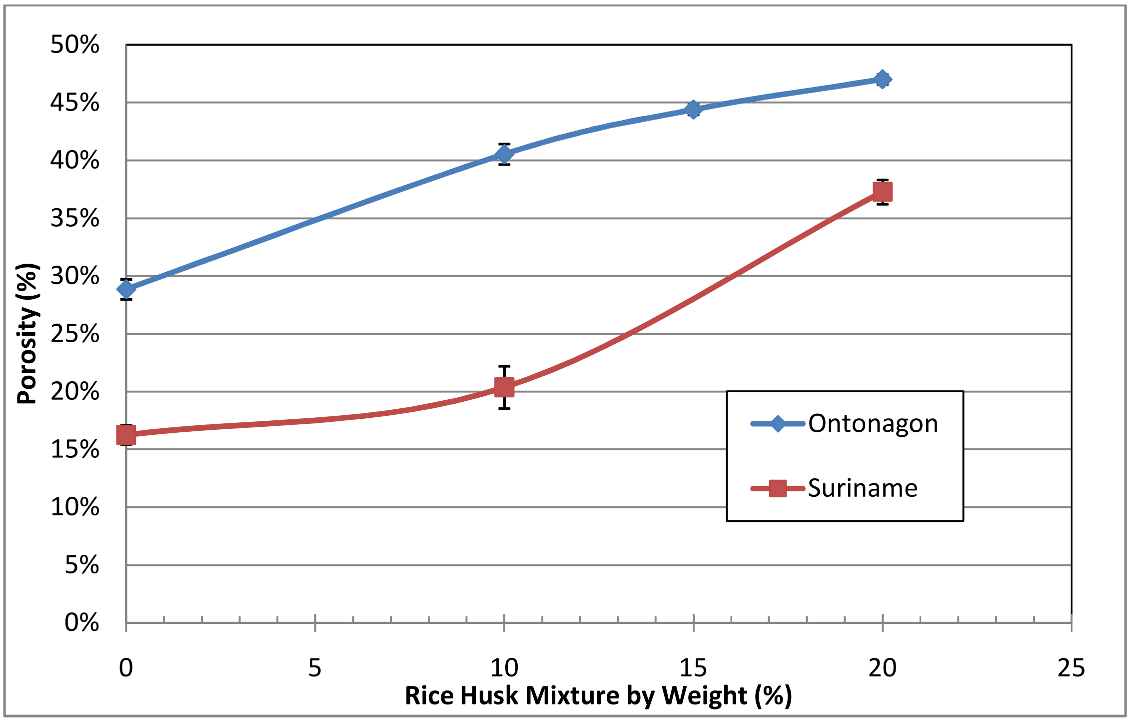


Figure 19: Average Porosity (n=4).

Figure 20 and Figure 21 show the results from the hydraulic conductivity tests for the Ontonagon and Suriname clay mixtures, respectively. Both clay types produced somewhat unexpected results. The Suriname 20% rice husk mixture and the Ontonagon 10% rice husk mixture both had relatively consistent results for each consecutive flush of distilled water and there was only marginal change in the hydraulic conductivity. The Ontonagon 20% rice husk mixture and the Suriname 10% rice husk mixture, on the other hand, produced significantly slower flow rates with each flush of water (these flushes are represented numerically in the figures below). In fact, during the second flush of distilled water through the Suriname 10% disks, after nearly 10 days, the water level had only dropped about 10 cm in the water column above the disk, whereas during the first flush the water level had dropped over 20 cm in less than seven days. A possible reason for these differences in hydraulic conductivity is clogging within the pores of the disks. Clogging may be due to particles (such as silica from the rice husk combustion) within the ceramic body being flushed from larger pores and then clogging the smaller pores in the filter.

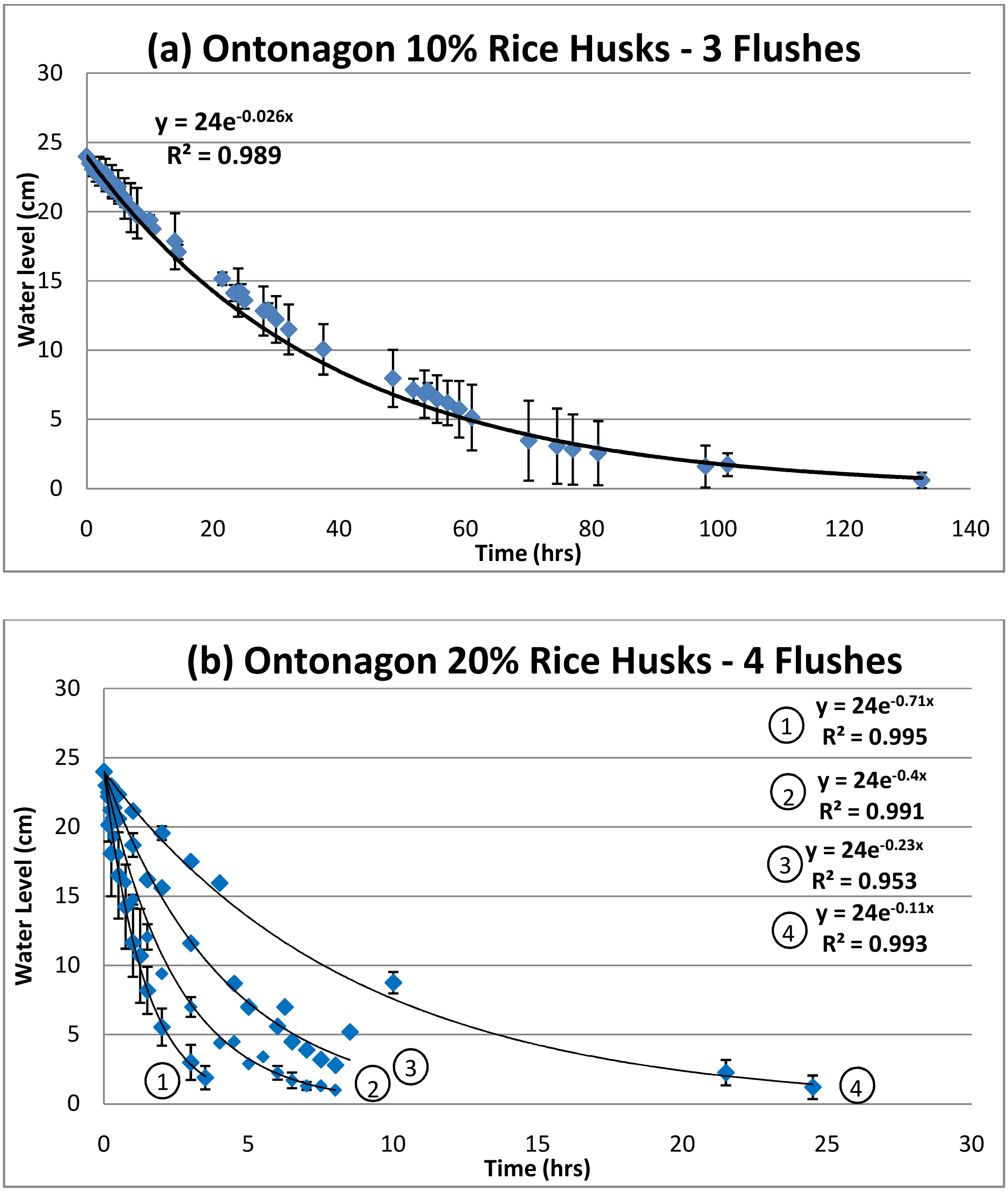
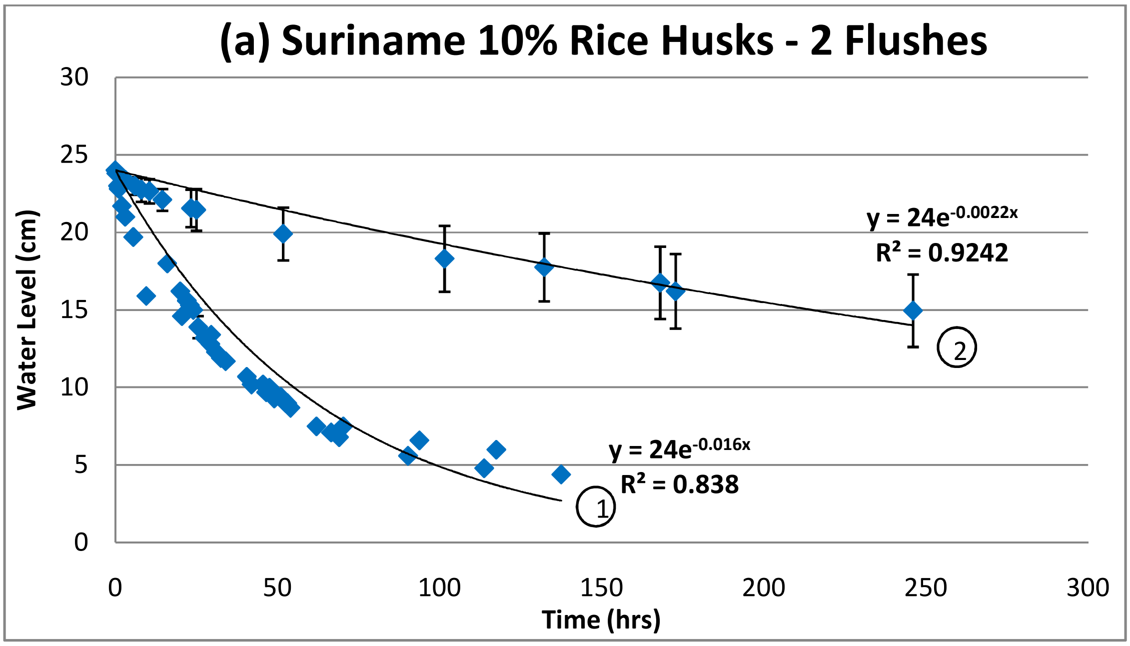


Figure 20: Falling-head test lab results for Ontonagon clay mixtures. Figure shows the average water level over time for each flush of water for 10% (a), and 20% (b) rice husk mixtures. The three disks constructed with the 10% rice husk mixture (n=3) underwent three flushes with distilled water. The data and trendline represent the average of the 9 tests. The two disks constructed with the 20% rice husk mixture (n=2) underwent four flushes with distilled water. Figure shows the resulting trendlines for the data sets. Trendlines were used to determine hydraulic conductivity (see Table 4).



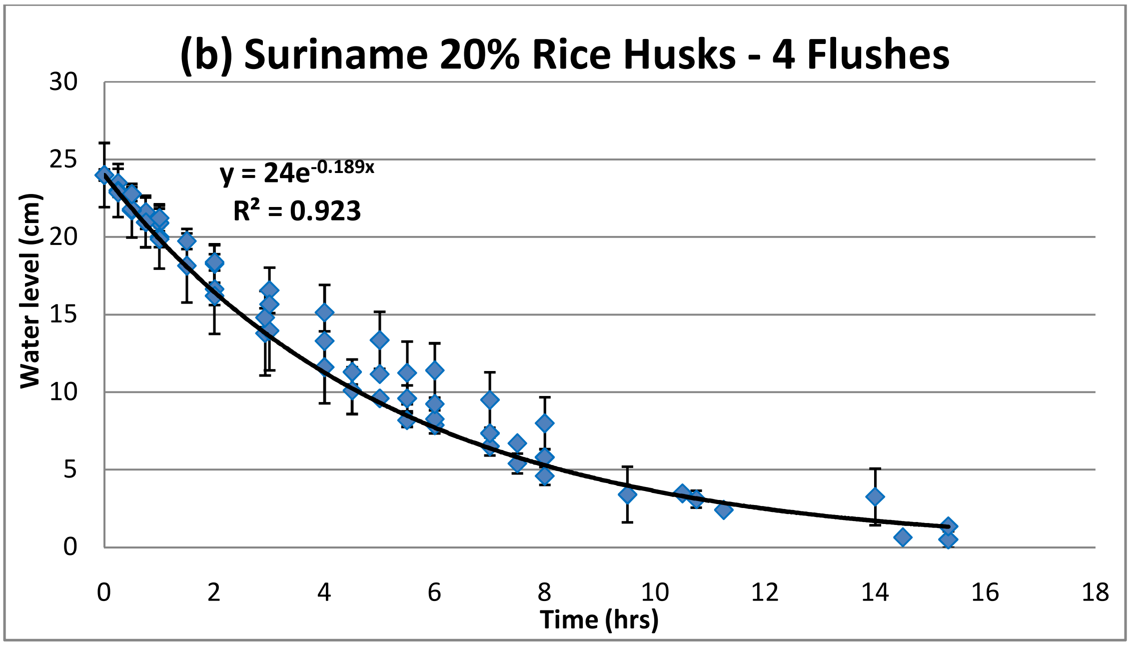


Figure 21: Falling-head test lab results with Suriname clay mixtures. Figure shows the average water level over time for each flush of water for 10% (a), and 20% (b) rice husk mixtures. The two disks constructed with the 10% rice husk mixture (n=2) underwent three flushes with distilled water. The three disks constructed with the 20% rice husk mixture (n=3) underwent four flushes with distilled water. The data and trendline represent the average of the 12 tests. Figure shows the resulting trendlines for the data sets. Trendlines were used to determine hydraulic conductivity (see Table 4).

The hydraulic conductivity calculated from the trendlines shown in Figures 15 and 16, and Equation 5, are tabulated in Table 4. Additionally, the expected flows through full-sized ceramic water filters were estimated with Equation 6 and the calculated hydraulic conductivity. A full-sized filter was assumed to be 24 cm tall with a base diameter of 30 cm and a top diameter of 32 cm. The thickness of the filter was assumed to be the same as the respective disk. PFP recommends flow rates between 1.5-2.5 L/hr. However, in a survey of 25 ceramic water filter factories around the world, it was found that accepted flow rates for operating factories ranged from 1.0-5.0 L/hr (Group 2011).

Table 4: Summary of hydraulic conductivity results. Table also shows the expected flow through a full-sized filter made from the respective clay/rice husk mixture when half full with water (h=12cm).

Mixture		*k* (cm/s)	*Q* filter (L/hr)
Ont 10%		1.66E-05	0.40
Ont 20%	1	4.79E-04	10.89
	2	2.70E-04	6.14
	3	1.55E-04	3.53
	4	7.43E-05	1.69
Sur 10%	1	9.02E-06	0.25
	2	1.24E-06	0.03
Sur 20%		1.28E-04	2.90

Once the hydraulic properties for each of the mixtures had been tested with distilled water, the disks were tested for their treatment effectiveness by measuring removal rates of *E. coli* and total coliform from contaminated water (results shown in Table 5). Both Ontonagon mixtures achieved 100% removal rates for both *E. coli* and total coliform, while the Suriname mixtures had more varied results. The Suriname clay mixture with 10% rice husks achieved 96.4% and 97.9% average removal rates for *E. coli* and total coliform, respectively. The Suriname clay mixture with 20% rice husks achieved 99.0% and 95.6% average removal rates for *E. coli* and total coliform, respectively. The average removal rates were determined by averaging the disk cycles of contaminated water. For example, there were 3 disks constructed from the Suriname clay mixture with 20% rice husks. So, for each cycle of contaminated water through the disks, there were three disk cycles. Figure 22 shows the results for all four sample cycles of contaminated water through the Suriname 20% rice husk mixture, which resulted in 12 total disk cycles that were averaged to find the values shown in Table 5.

Table 5: Summary of ceramic filter treatment effectiveness results. The summary includes the average for each disk cycle of contaminated water.

		Percent Removal	
		E. coli	Total Coliform
ONT 10%	Average	100	100
(n=15)	StDev	0	0
ONT 20%	Average	100	100
(n=10)	StDev	0	0
Sur 10%	Average	96.4	97.9
(n=2)	StDev	5.05	0.19
Sur 20%	Average	99	95.6
(n=12)	StDev	2.54	6.95

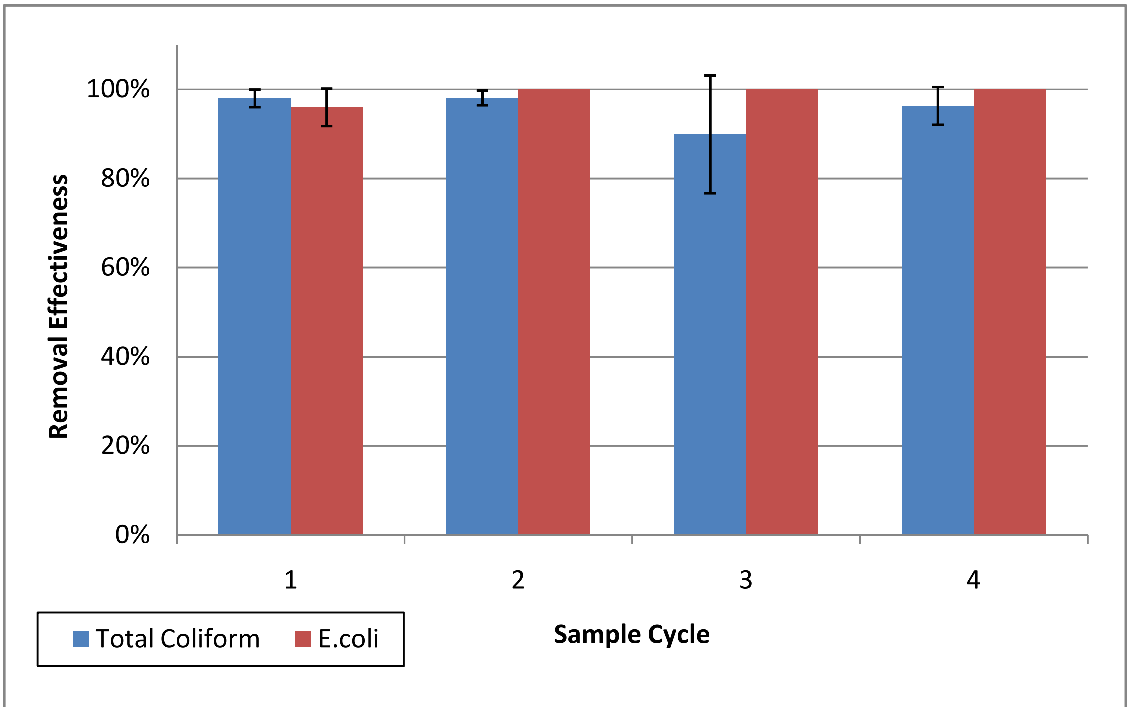


Figure 22: Treatment effectiveness results for Suriname clay mixture with 20% rice husks by weight. Figure shows the average removal rates for the four cycles of contaminated water through the three disks (n=3).

Figure 23, Figure 24, and Table 6 summarize the treatment effectiveness results from the testing done on the Bendekonde water treatment system in 2011. Figure 23 illustrates the treatment effectiveness results from the samples collected after the rapid sand filtration process, before the slow sand filter. On average, the water flowing into the slow sand filter (see Figure 17) contained 21% higher *E. coli* contamination than the untreated river water but reduced total coliform by 30%. The system as a whole consistently achieved 100% removal of *E. coli,* and averaged 76% removal of total coliform. As Figure 24 illustrates, there was significantly more variation in the removal rates of total coliform as compared *to E. coli* depending on the day of sampling. Figure 25 depicts the *E. coli* and total coliform contamination levels in the Suriname River water prior to entering the treatment system.

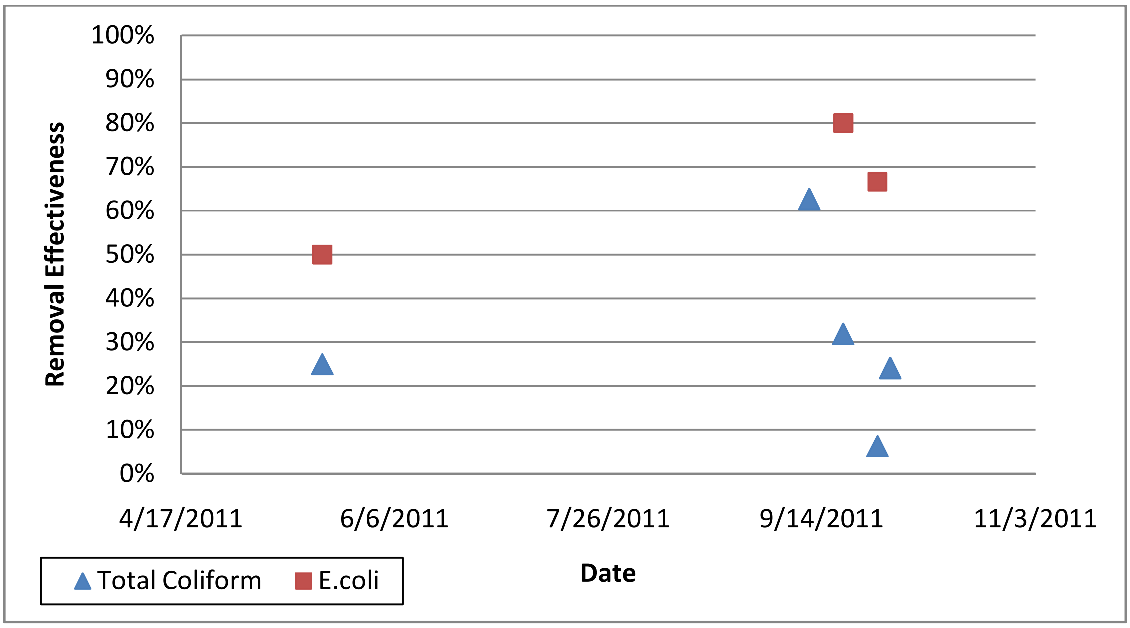


Figure 23: Treatment effectiveness results after rapid sand filtration in Bendekonde. Results are from field testing performed in 2011 and show the removal rates for *E. coli* and total coliform after the rapid sand filter, before the slow sand filter. NOTE: Two samples in September (not shown here) indicated an increase in *E. coli* contamination by 200%.

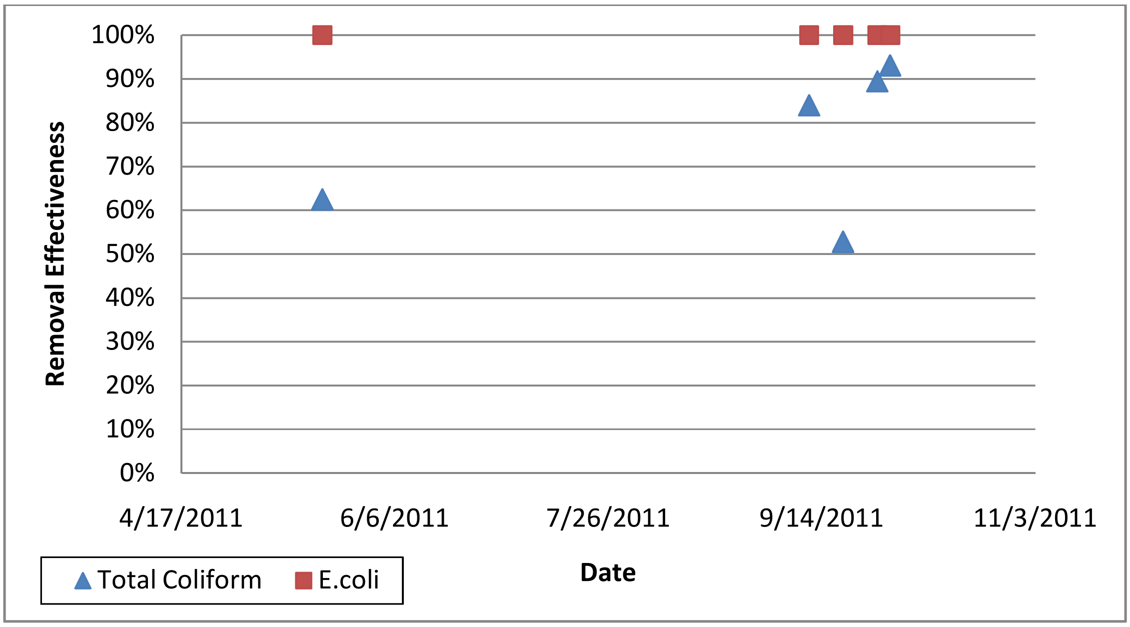


Figure 24: Total treatment effectiveness results for Bendekonde Water Treatment System as measured at a tap. Results are from field testing performed in 2011 and show the removal rates for *E. coli* and total coliform.

Table 6: Summary of treatment effectiveness of the Bendekonde Water Treatment System. Table shows the average removal rates of *E. coli* and total coliform.

		Percent Removal	
		E. coli	**Total Coliform**
After RS before SS	Average	-21	30
(n=5)	StDev	124	21
Whole System	Average	100	76
(n=5)	StDev	0	18

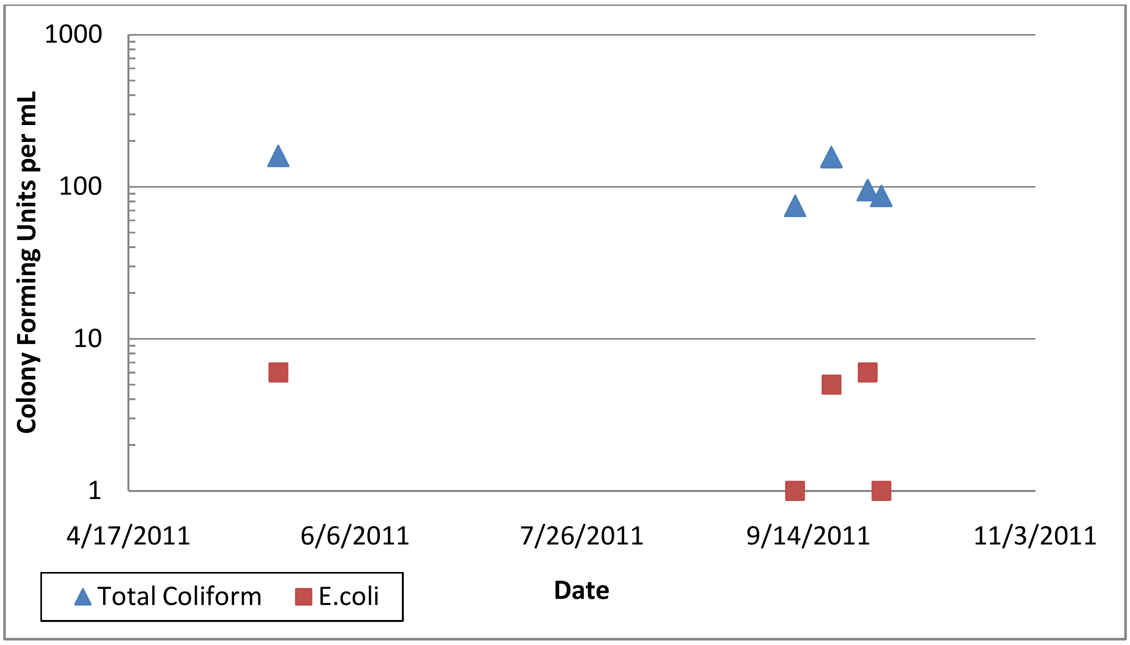


Figure 25: Bendekonde influent contamination levels. Data reflects results from tests performed in 2011 on untreated river water before entering the Bendekonde water treatment system.

6.0 DISCUSSION

The first objective of this study was to investigate the physical characteristics of local Surinamese clay and the possible applications to the production of ceramic water filters. The results of the plasticity and shrinkage tests ranged within either the recommended values found in the PFP Best practices manual (as was the case for the plasticity results) or the reported values from operational factories (as seen in the total shrinkage results). The porosity results showed that the Suriname 20% rice husk mixture was within other documented values for functional filters (Van Halem 2006). The porosity of the filters was directly affected by the ratio of rice husks added to the mixture. By testing mixtures with varying percentages of rice husks, the porosity values could be further adjusted. While porosity is a useful piece of information when producing filters, it is not a defining characteristic; hydraulic conductivity and treatment effectiveness are much more critical in determining the appropriateness of a filter or mixture. The hydraulic conductivity results showed that a full-sized filter made from the Suriname 10% rice husk mixture would likely produce flow rates between 0.03-0.25 L/hr, well below the recommended values (1.5-2.5 L/hr) or recorded values (1.0-5.0 L/hr). The Suriname 20% rice husks mixture on the other hand would likely produce a filter with a flow rate around 2.9 L/hr which, while outside the PFP recommended values, is well within the recorded values from operating factories.

The second objective of this study was to compare the treatment effectiveness of the Bendekonde water treatment system to that of ceramic water filters made from local Suriname clay. Results from testing on the Bendekonde system and on the ceramic disks showed that the Bendekonde system was more consistently effective at removing *E. coli* from influent waters, achieving 100% removal compared to 96.4-99.0% achieved by the ceramic disks. The ceramic disks achieved higher average removal rates of total coliform with 95.6-97.9% removal compared to 76% removal for the Bendekonde system. The reasons for the varying removal rates are likely due to the treatment effectiveness of the two systems, but other factors may also be influencing the results. It is possible that the total coliform present in the tap water in Bendekonde was the result of infiltration in the distribution network as opposed to ineffective or incomplete treatment. Post-treatment contamination is a recognized risk when employing centralized treatment due to the distance traveled by the water from the source (tap or treatment facility) to the point of use (household) (Wright 2004). Technologies such as ceramic water filters reduce the risk of post treatment contamination as the water is treated at the point of use. Even though the Bendekonde system effectively removed *E. coli*, the total coliform contamination raises an interesting concern. Would the water treated by the Bendekonde system be as clean as that treated by a ceramic water filter when it reached the household? Analyzing post-treatment contamination was not part of this study, but is an important aspect to consider when implementing a new technology. Are the living conditions and hygiene practices of the community going to maximize the treatment technologies' ability to deliver safe clean water to the point of use?

The Bendekonde system, with its composite parts, was effective at removing *E. coli,* and moderately successful at total coliform removal. However, were a given element to be removed from the system or become in-operational, it is questionable whether the system would continue to successfully treat water. The results from the 2011 testing showed that water having already passed the rapid sand filter but prior to flowing through the slow sand filter, was often more contaminated than untreated river water. This may be due to inadequate maintenance of the filter, or varying influent contamination levels as the river contamination changes as the river flows. The decreasing water quality after rapid sand filtration is important to note for two reasons. First, pressurized rapid sand filters have been implemented in other communities along the Upper Suriname River as the sole treatment technology. For example, Botopasi is a relatively large village in the region and has a rapid sand filter installed as the only means of treatment, and the system has been used as an example of a system to be emulated in other areas. Yet, the results from Bendekonde illustrate a filter similar to that in Bendekonde may in fact be degrading the water quality. Second, were an element of the Bendekonde system to fail, the water treatment ability of the system would be compromised.

In 2012 Moilanen performed a life-cycle assessment (LCA) comparing the Bendekonde system to locally and regionally produced ceramic water filters. In this comparison it was found that both scenarios for ceramic filter production had significantly lower expected cumulative energy demand as well as global warming potential. However, due to the environmental impacts of firing the filters in wood burning kilns, the solar powered system of Bendekonde scored lower for ecosystem damage potential (Moilanen 2012). This information should also be considered by organizations when considering priorities for drinking water projects.

When comparing the treatment effectiveness of the two Suriname clay mixtures, somewhat surprisingly, the 20% rice husk mixture was more effective at removing E. coli than the 10% mixture. A challenge when interpreting these results however is the limited samples tested from the 10% mixture. As shown in the hydraulic conductivity testing, the flow rate of the

Suriname 10% rice husk mixture became incredibly slow during the second flush of distilled water. Once the contaminated water cycles were started, the flow rate became even slower, such that that effluent samples could not be collected within 10 hours of initiating flow.

After testing was completed with the disks in the column set-up, the disks were removed from the coupling and cut in half in order to attempt to better understand the variations in effectiveness of the two Suriname clay mixtures. Disks from both mixtures had a black core, indicating that the carbon present during the firing process had not completely burned out. The reason for incomplete firing in this case is possibly due to insufficient ventilation within the muffle furnace. Carbon and activated carbon are known to remove contaminants from water and have been popularly used to make filters for water purification. However, the effects of the carbon cores on the performance of ceramic water filters have yet to be investigated. Finally, one thin section from each of the disks was made and analyzed using Leica Microsystems (Buffalo Grove, IL) LAS image analysis. A summary of the results and examples of the images can be found in Appendix B. The images were used to determine average pore sizes by measuring the longest dimension of each of pore. The results show that while the 20% mixture on average had higher quantities of pores in the ceramic body, the 10% mixture had larger pores sizes on average. The larger pores in the 10% mixture help to explain the reduced treatment ability of the mixture.

7.0 CONCLUSIONS

The Suriname clay assessed in this study is appropriate for the production of ceramic water filters. Results from the physical properties testing of the various mixtures showed that the plasticity, shrinkage, and porosity were within reasonable ranges, indicating that manufacture and production of filters would be viable. In addition, the hydraulic conductivity achieved by the 20% rice husk mixture was within an acceptable range.

The Bendekonde system as a whole was more effective than both the Suriname clay mixtures at removing *E. coli* but was less effective at removing total coliform. However, the ceramic point-of-use filter would likely result in less contamination in household water as the treated water would travel less distance after treatment. In addition, by including colloidal silver in the filter design, the treatment effectiveness ceramic filter could be improved (Lantagne 2001; Oyanedel-Craver 2008).

Relying on local materials, ceramic water filters provide a simple technology that should be considered for remote communities like those along the Upper Suriname River. Not only do they offer an alternative to the currently installed and commonly failed centralized treatment options, ceramic filters could also create revenue for locally trained artisans in a region mostly devoid of economic opportunities. The implementation of a ceramic filter workshop or factory would require a significant amount of work and investment before any production could begin, but in the long run, the factory could eventually become completely self-sustaining without any outside aid or subsidy.

8.0 RECOMMENDATIONS FOR FUTURE WORK

A wider range of rice husk to clay mixture ratios could be investigated to more fully understand possibilities for ceramic water filters made from the Surinamese clay. The varying mixture ratios would allow not only for possible adjustment of the hydraulic conductivity and treatment effectiveness, but also the workability of the products. Also, in this study the disks were compressed at a pressure of 100 psi. PFP has reported that the effect the applied compressive pressure has on filter performance is yet to be fully understood and remains an area to be researched further (Group 2011).

Post-treatment contamination of drinking water is an issue that has not been researched or quantified in Saramaccan communities. In general, cleanliness of the home and body are highly valued socially within the Saramaccan culture. However the sanitation practices and lack of improved facilities creates an environment with many pathways for contamination and re-contamination, as most washing (dishes, hands, water storage containers, clothes, etc.) is done with untreated river water. Even in villages such as Bendekonde with operational water treatment systems and wash stations, women will often choose to wash at the river as it is where many are more accustomed.

Prior to attempting to implement a ceramic water filter program, the social acceptability of the technology should be formally investigated. The author had the opportunity to informally interview several people from Bendekonde and other surrounding villages about general perception of, and possible receptiveness to, the filters, and heard mostly positive feedback. These interviews and impressions should be developed further in a more official and systemized manner to ensure any program implementation is organized for maximum social acceptability.

The reasons for the variations in the treatment effectiveness of the 10% and 20% rice husk mixture with the Suriname clay are not fully understood. It is possible that the carbon present in the under-fired disks played a role. Testing the treatment effectiveness of filters fired at different temperatures and durations would help to quantify the influence the carbon core may have had on filter performance.

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APPENDIX A

Medical Mission Data Report:

Incidences of Diarrhoea on the Upper Suriname River, Suriname (2000-2009)

By: Ashlee Vincent

Background:

Improving water, sanitation, and hygiene (WASH) practices and facilities in the interior of Suriname is a major objective of many ministries and NGO's in the capital, Paramaribo. The goals of WASH projects are ultimately to improve the public health of the communities. However, little research has been done to show what the public health issues are in Suriname regarding water borne illness. For example, what are the seasonal patterns of diarrhoea, are some communities more susceptible to higher incidences of diarrhoea, and is there any correlation for villages with low incidences of diarrhoea? Much of the information currently available regarding these questions is anecdotal at best and non-existent at worst.

Most of the communities on the Upper Suriname River rely solely on the river and various creeks for all their water demands. Some villages have been equipped with water treatment systems, few of the systems installed are actually operating, and only a few of those operating seem to be treating water successfully. Otherwise, community members must strategically utilize surface water as the seasons change, and thus the quality of water changes, to meet their daily needs. It is commonly stated by villagers that they notice increased illnesses during the dry seasons (Aug-Nov, Feb-April), particularly the long-dry season.

A common practice on the Suriname River is to alternate drinking water sources depending on the season. There are many creeks that feed into the river, and they are typically preferred by villagers for drinking water. Most people do the majority of their washing and bathing directly in the river itself and the river is often the location villagers will go to defecate. Clearly, the river has a greater likelihood of being contaminated than the creeks. During the rainy seasons people utilize creeks and rainwater catchment for their drinking water needs. Unfortunately, these sources are not reliable throughout the dry season; the creeks often go dry and the storage capacity of the catchment basins is not sufficient. During the dry season many people resort to river water for drinking, even though most are aware of the risks. Some will take measures to improve the quality of the water (i.e. boiling, filtering) but these are not typical practices in the culture.

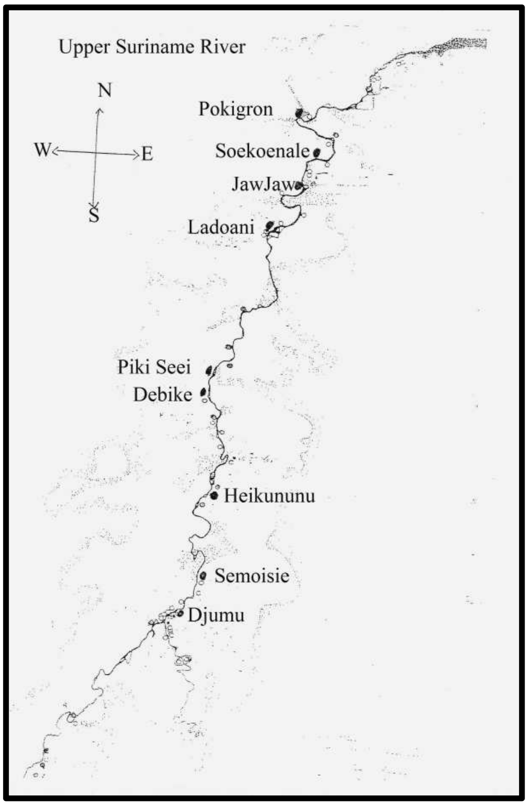


Figure 1: Medical Mission Health Clinics on the Upper Suriname River.

There are a total of nine health clinics, locally called poli clinics, along the upper Suriname River. The clinics are operated by Medische Zending (Medical Mission), a private, non-profit, primary health care organization. MZ has been operating clinics in the interior since the 1950's and has had a long established history in Suriname. However, due to the fighting that occurred in the late 1980's and early 1990's, they have little records dating before 2000. Since 2000, MZ clinics in the interior have reported to headquarters weekly incidences of various illnesses and conditions (i.e. malaria, dengue, HIV, diarrhoea). See Figure 1 above for a map showing the locations of the MZ health clinics on the Upper Suriname River.

Purpose:

The purpose of this report is to summarize and analyse the weekly incidence of diarrhoea on the Upper Suriname River, as reported by Medische Zending, in order to better understand the public health situation in the region as it pertains to water, sanitation, and hygiene.

Methodology:

MZ provided weekly incidences of diarrhoea, per clinic, from 2000-2009. In a few of the clinics there are gaps in weekly reports, possibly due to staffing shortages, but 5 of the 9 clinics have complete data (Semoisie is missing weeks 6-10 and 52 of 2001, Soekoenale is missing weeks 33-52 of 2000, Heikununu is missing weeks 1-3 of 2001, and Pikiseei is missing weeks 1-4 of 2001). The numbers of weekly incidences are reported as raw numbers, ranging from zero incidences in a week, to as high as 63 incidences. Comparing data from various clinics can be misleading however due to the fact that each clinic serves a given population, each of a different size. To address this difference, MZ provided the yearly numbers of registered patients per clinic from 2001-2009. The registered number of registered patients for 2000 was unavailable, so the same number recorded for 2001 was also assumed for 2000. To equalize the data provided from the clinics, the weekly incidences of reported diarrhoea were divided by the number of registered patients for the year of the given clinic. The numbers were then reported in incidences per 100 registered patients.

Results:

First, the yearly totals for each clinic were compared to examine if there are any trends, or any clinics that typically observe higher incidences of diarrhoea. A graph showing yearly incidences of diarrhoea is shown below in Figure 2. Between 2001 and 2003 there appears to have been conditions that lead to a dramatic increase in incidences in several of the clinics, and then potentially an intervention that counteracted the outbreak. Aside from the sharp increase in 2002, there is minimal difference in number of incidences between clinics along the river.

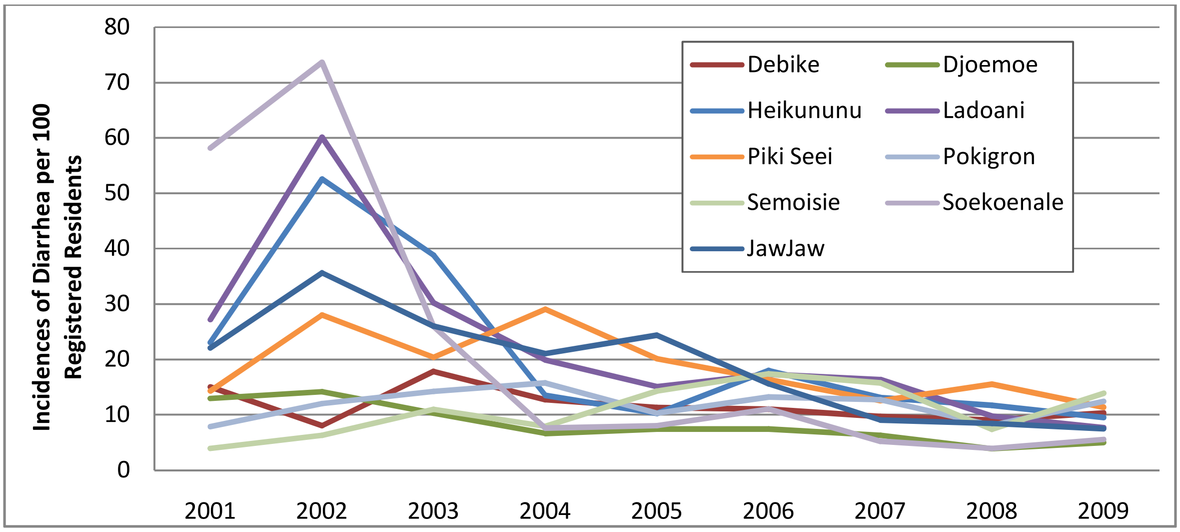


Figure 2: Yearly Incidences of Diarrhea on the Upper Suriname River per MZ Policlinic

Next, seasonal variations of the clinics were investigated by averaging each week's incidences over the ten year time frame. Most of the health clinics showed a general increase in incidences during both dry seasons, and decreases during the wet seasons. Figure 3 illustrates the seasonal trend for one clinic, Djumu, as compared to the average of all 9 clinics on the Upper Suriname River. Though these variations in number of incidences are relatively small, nearly all of the clinics on the Upper Suriname River display the general patterns shown below in Figure 3. Djumu averages slightly fewer cases of diarrhea weekly than typically seen on the rest of the river, and follows the average river trend very closely. Other clinics however show greater variations and peaks weekly than the river average, or than Djumu. An example is illustrated in Figure 4 which shows the weekly averages for Heikununu as compared to the river average.

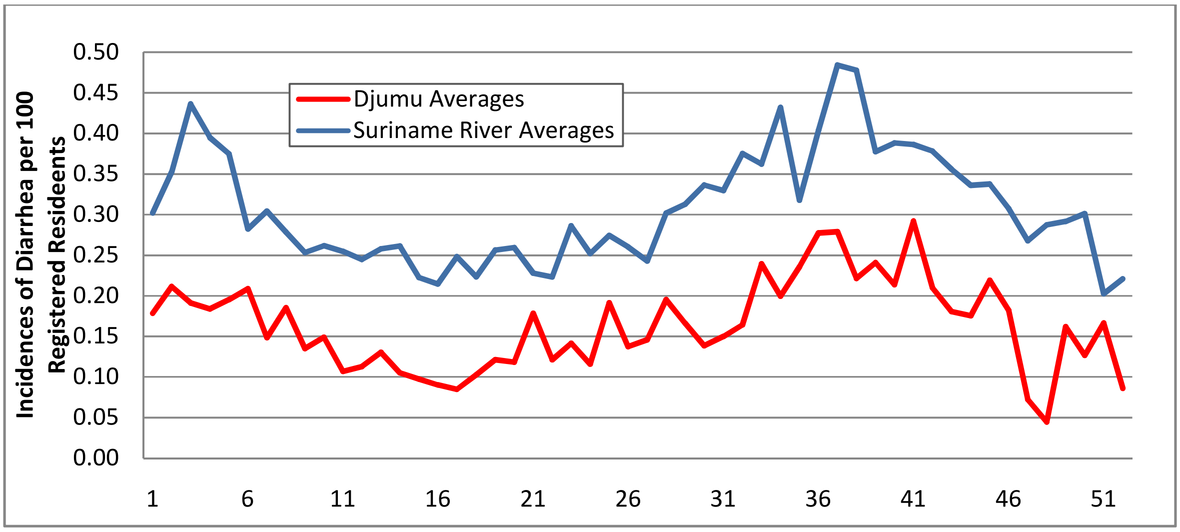


Figure 3: Average weekly incidences of diarrhea at MZ health clinic Djumu compared to the average weekly incidences for all 9 clinics on the Suriname River. Weeks are shown on the “X” axis. The dry seasons occur between weeks 6 thru 15, and again from weeks 33 thru 46.

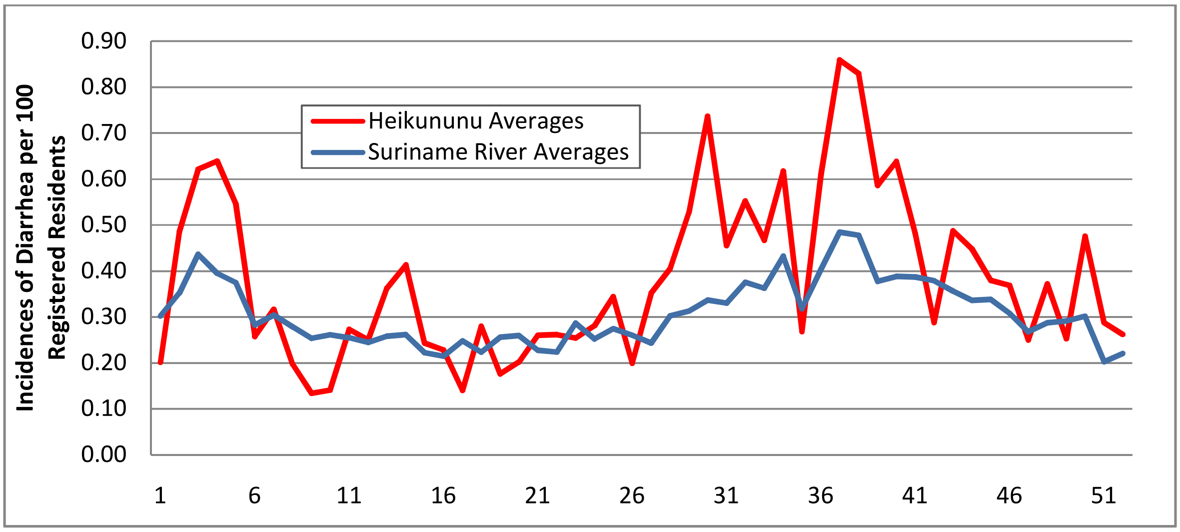


Figure 4: Average weekly incidences of diarrhea at MZ health clinic Heikununu compared to the average weekly incidences for all 9 clinics on the Suriname River. Weeks are shown on the "X" axis. The dry seasons occur between weeks 6 thru 15, and again from weeks 33 thru 46.

To further investigate the seasonal averages, the week which averaged the highest incidences of diarrhea between 2000 and 2009 was noted for each clinic. See Table 1 for values and corresponding week (note, the long dry season occurs between weeks 33-46).

Whereas Djumu shows very slight changes from week to week (as shown in Figure 3), other clinics showed a much greater variation and drastic changes throughout the year. Figures 5 and 6 show the number of weeks from 2000 to 2009 with zero reported cases of diarrhea per clinic, and the average weekly reported number of cases, respectively.

Table 1: Average Highest Weekly Diarrheal Incidence between 2000 and 2009

MZ Clinic	Incidence/100 people	Week
Debike	0.529	39
Djumu	0.292	41
Heikununu	0.859	37
JawJaw	0.905	38
Ladoani	0.812	3
Piki Seei	0.576	34
Pokigron	0.50	37
Semoisie	0.431	41
Soekoenale	0.639	11

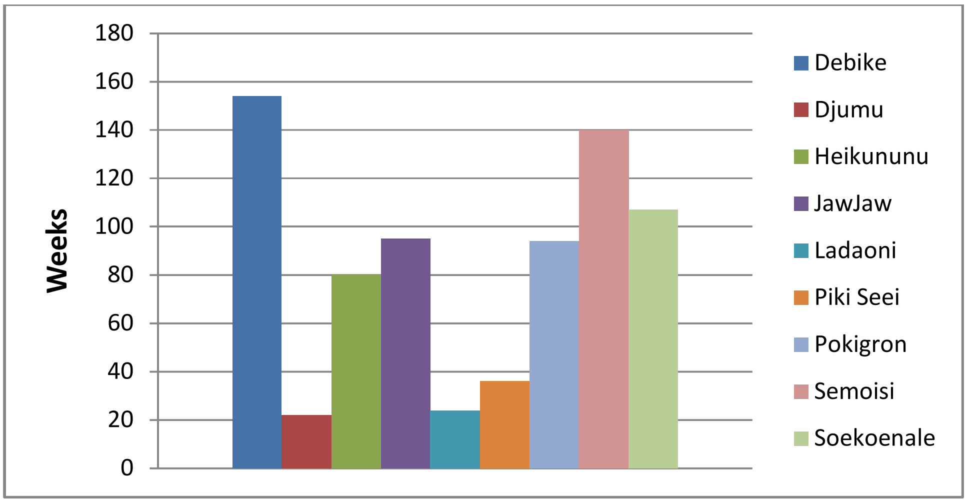


Figure 5: Weeks with Zero Reported Cases of Diarrhea between 2000 and 2009

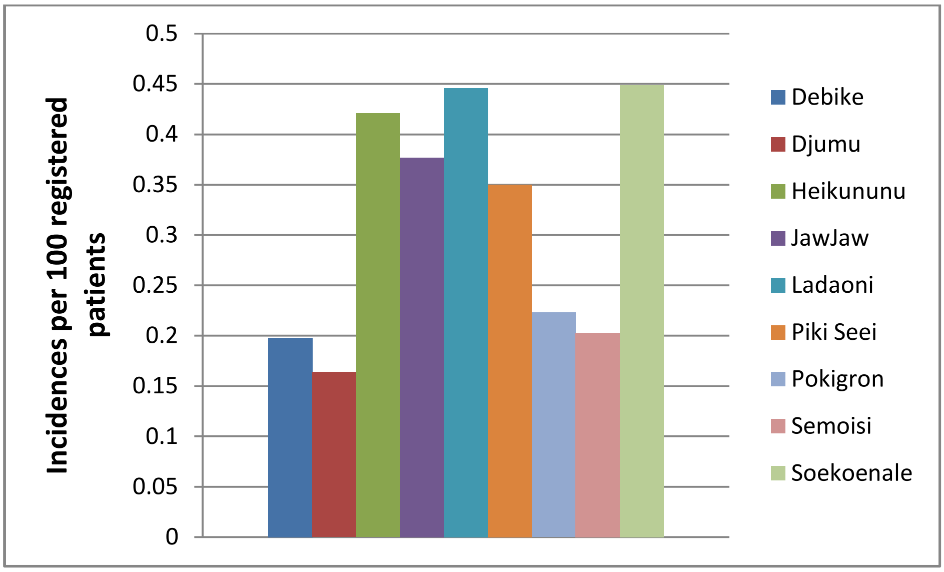


Figure 6: Average Weekly Reported Incidences of Diarrhea (2000-2009)

APPENDIX B

The results below are reflective of six Leica LAS image analyses (Buffalo Grove, IL) produced from one thin section cut from a disk made from the respective clay rice husk mixtures. The averages were obtained by summing the total lengths from each of the 6 images, and dividing it by the sum of the total counts from each image. These results show that while the 20% mixture on average had higher quantities of pores, the 10% mixture had larger pores on average. The larger pores in the 10% mixture help to explain the reduced treatment ability of the mixture. Examples of the LAS reports from each mixture are shown on the following pages

Suriname 10%

Image	Total Length (µm)	Total Count	Mean (µm)
1	16752	257	65.18
2	12302	142	86.63
3	13739	139	98.84
4	14318	147	97.40
5	10989	151	72.77
6	15549	238	65.33
TOTAL	83649	1074	

Average Length	**77.89**	**µm**
Average Total Count	**179.00**	

Suriname 20%

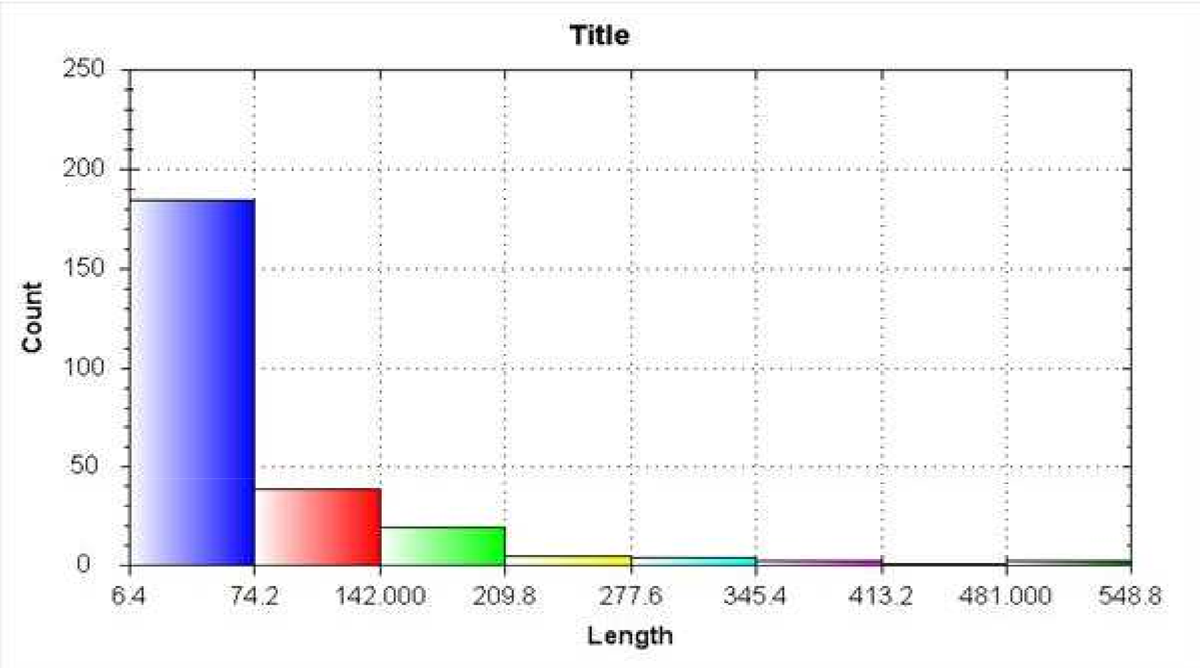
Image	Total Length (µm)	Total Count	Mean (µm)
1	23466	364	64.47
2	20312	346	58.71
3	19861	289	68.72
4	20086	290	69.26
5	13619	216	63.05
6	15459	234	66.06
TOTAL	112803	1739	

Average Length	**64.87**	**µm**
Average Total Count	**289.83**	

SUR 10%
Histogram Statistics

3in Statistic:	Value
'size Count	0.00
Total Count	257.00
'size Count	0.00
Total (µm)	16752.00
Mean (µm)	65.18
td Dev (µm)	81.38
1 Error (µm)	5.08
ximum (µm)	548.80
nimum (µm)	6.40
Range (µm)	325.54
Median (µm)	40.30
Mode (µm)	40.30
Skewness	2.74
Kurtosis	9.55
Features	257.00
1 Area (µm²)	8053064
lised Count	31.91
it Count (%)	0.00

Histogram Chart

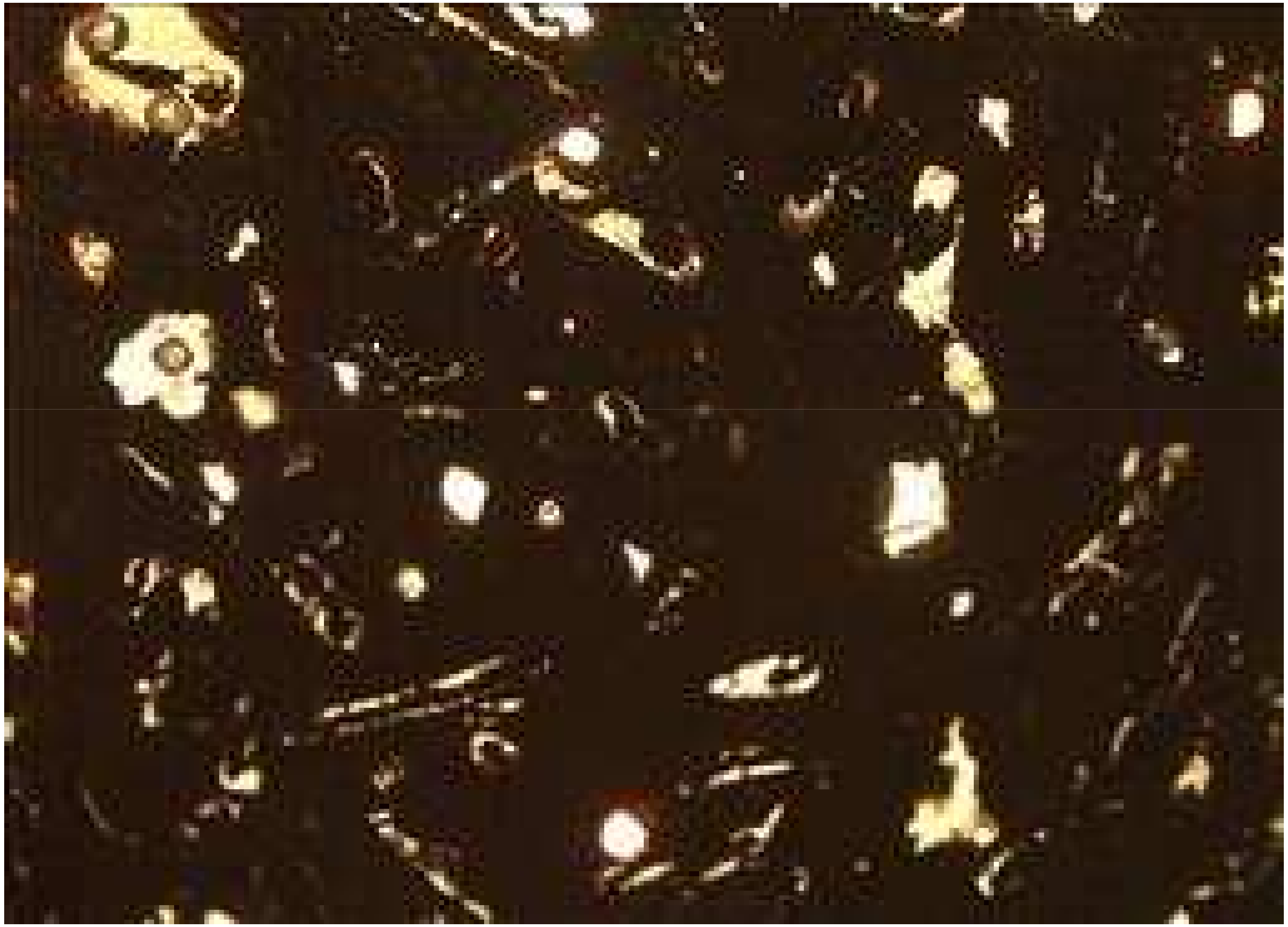


Bin Data

Bin	Length(µm) Lower	Length(µm) Upper	Count	Count1	Percent of Total Count	
1	6.4	74.2	185	185	71.984	
2	74.2	142.	39	39	15.175	
3	142.	209.8	19	19	7.393	
4	209.8	277.6	5	5	1.946	
5	277.6	345.4	4	4	1.556	
6	345.4	413.2	2	2	0.778	
7	413.2	481.	1	1	0.389	
8	481.	548.8	2	2	0.778	64.

SUR 10%

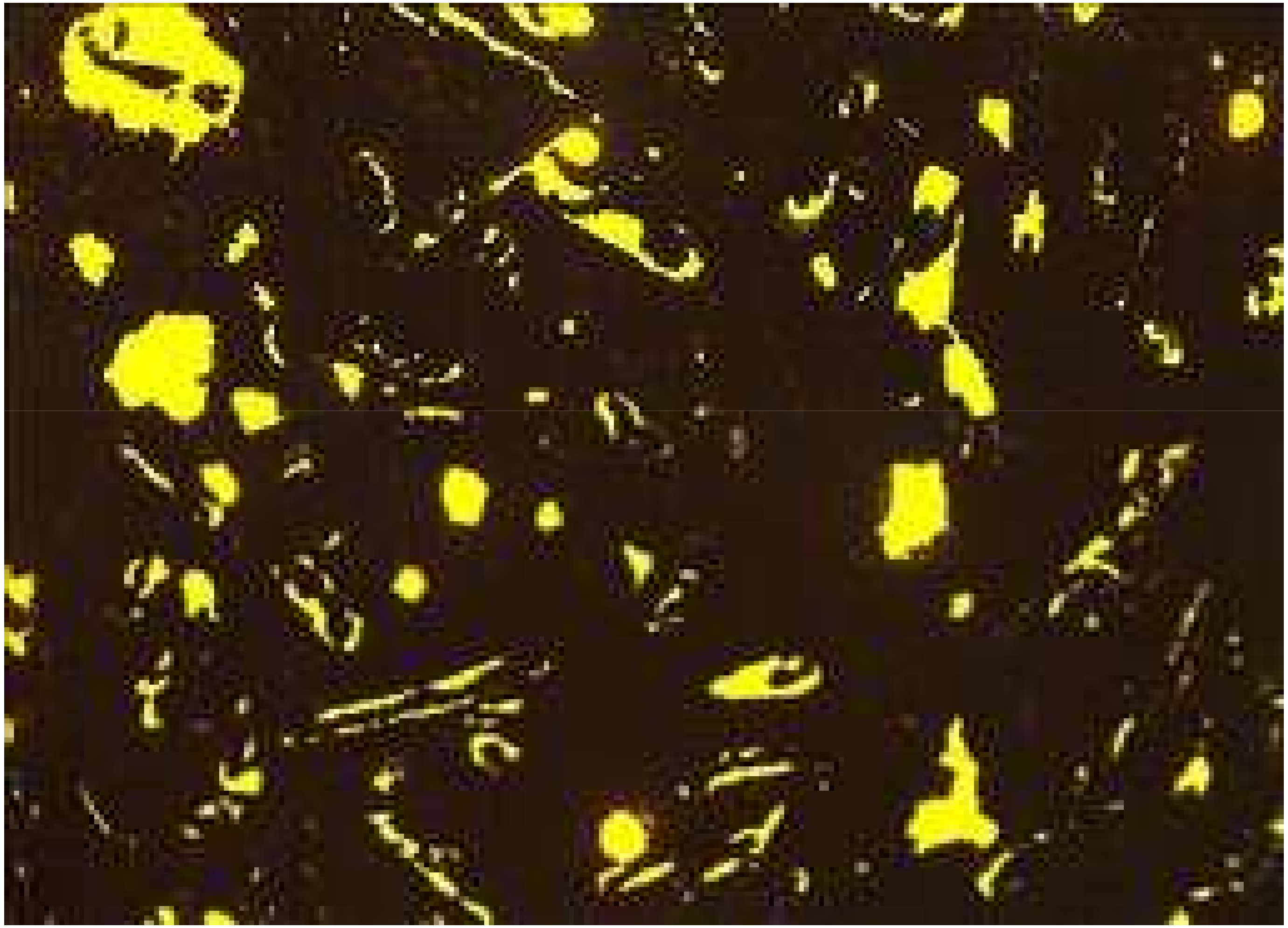
image0041.tif



Unenhanced image of the thin section. The small circular bubbles are a result of the epoxy used to make the thin sections.

SUR 10%

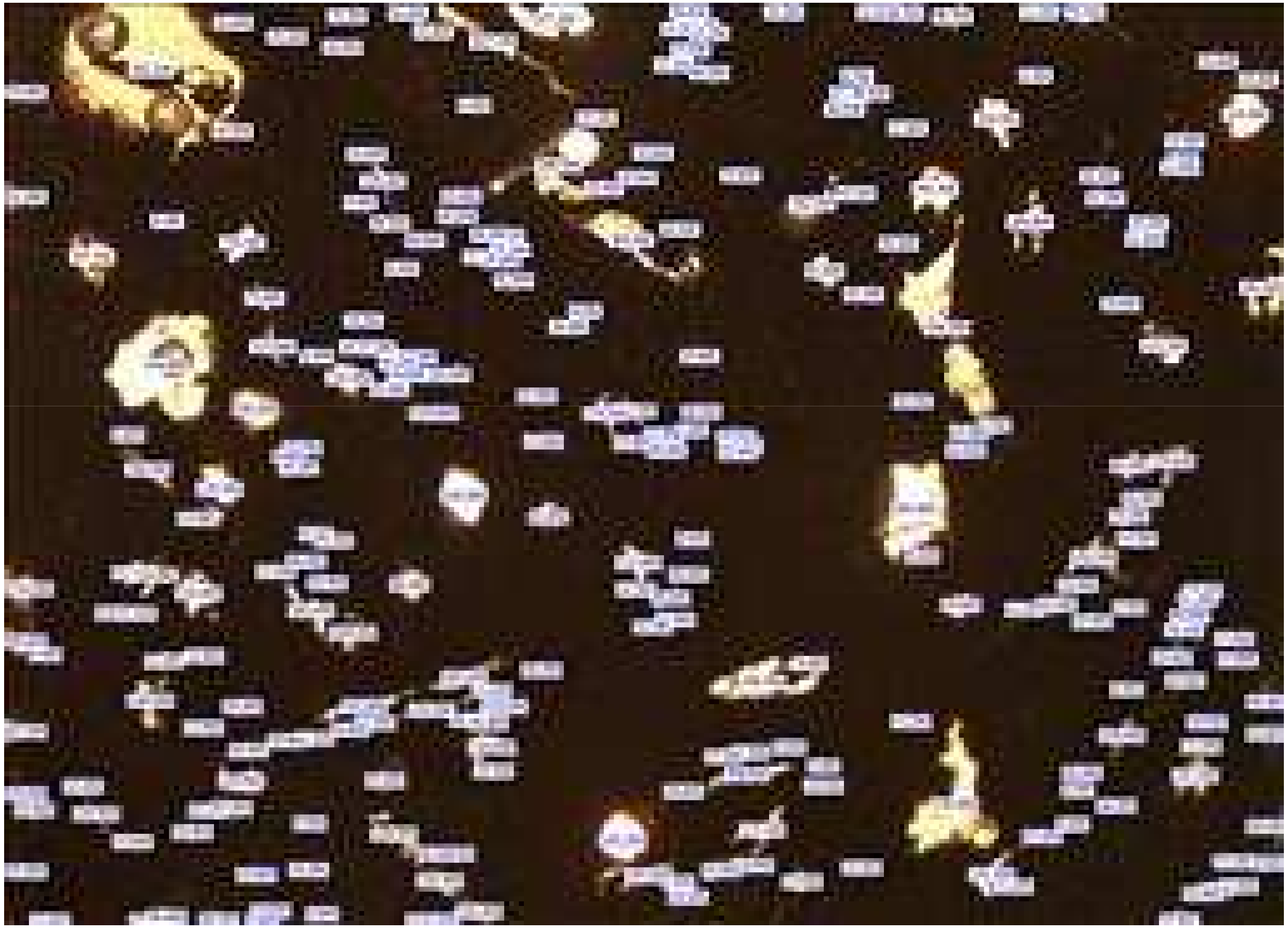
image0041.tif: Binary Mask



A binary mask is used to detect the pore spaces and allow the program to measure the longest dimension. The small circular bubbles are a result of the epoxy used to make the thin sections.

SUR 10%

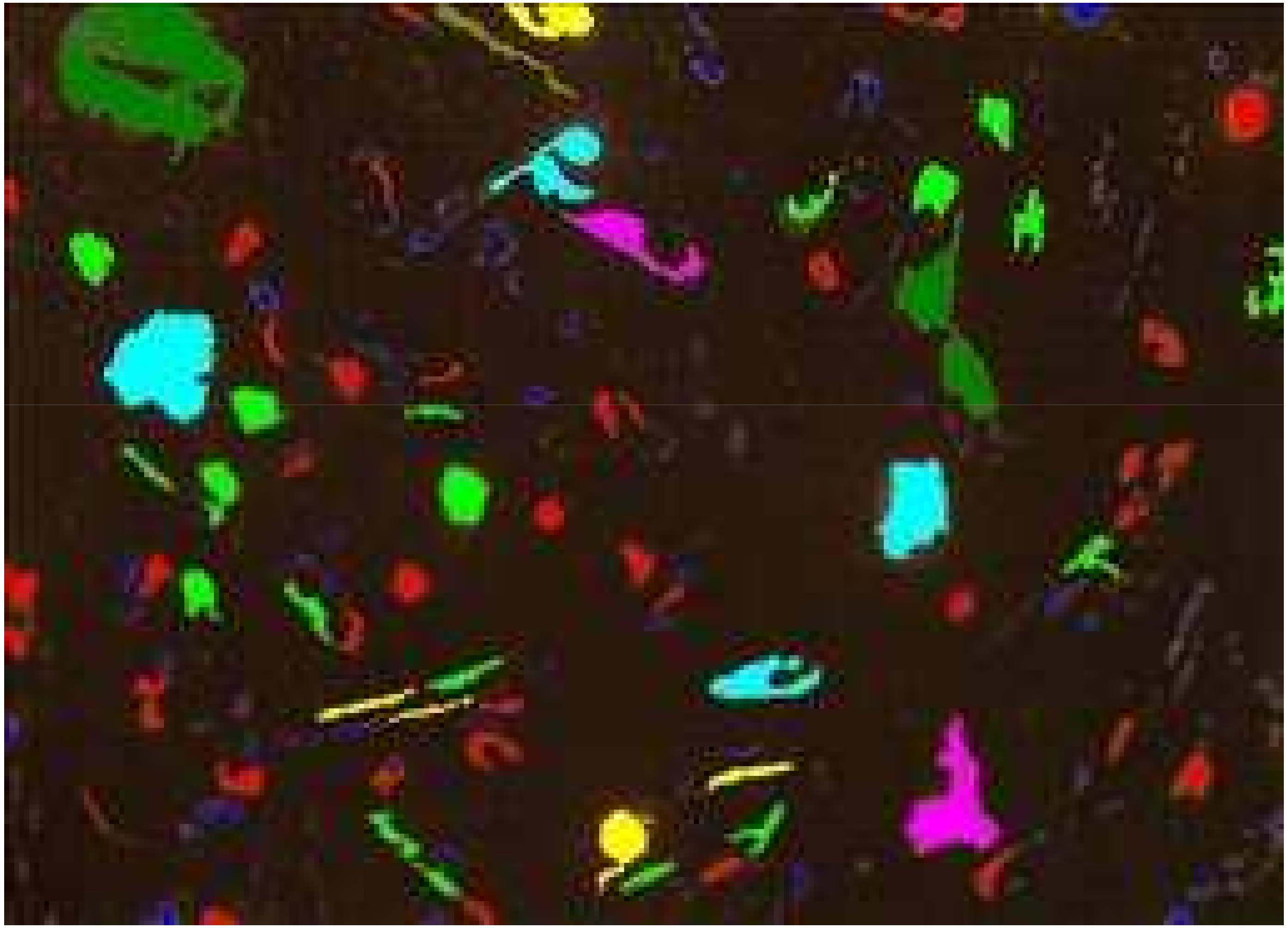
image0041.tif: Labels



Measurements for the longest dimension of each of the pore spaces.

SUR 10%

image0041.tif: Colour Coded



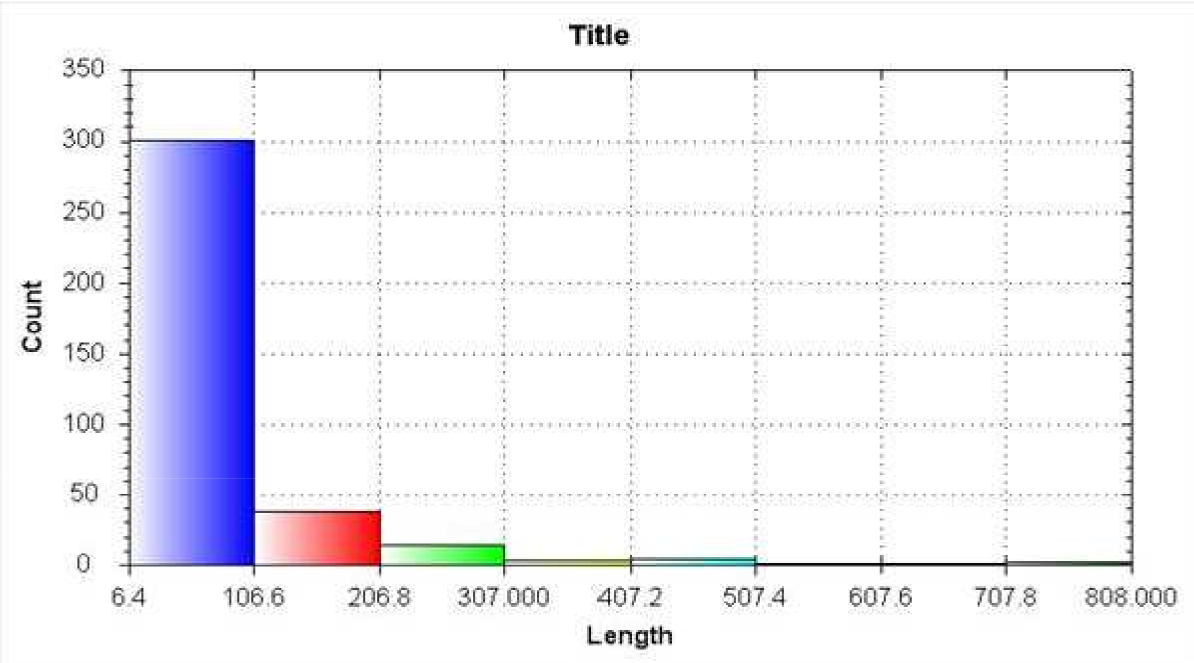
Pore spaces are color coded based on size. Colors match the colors of the bins in the histogram.

SUR 20%

Histogram Statistics

Bin Statistics	Value
rsize Count	0
Total Count	364
rsize Count	0
Total (µm)	23465.6
Mean (µm)	64.466
td Dev (µm)	101.785
d Error (µm)	5.335
ximum (µm)	808.
nimum (µm)	6.4
Range (µm)	407.142
Median (µm)	56.5
Mode (µm)	56.5
Skewness	3.892
Kurtosis	19.664
Features	364
n Area (µm²)	8053064
lised Count	45.2
nt Count (%)	0.005

Histogram Chart

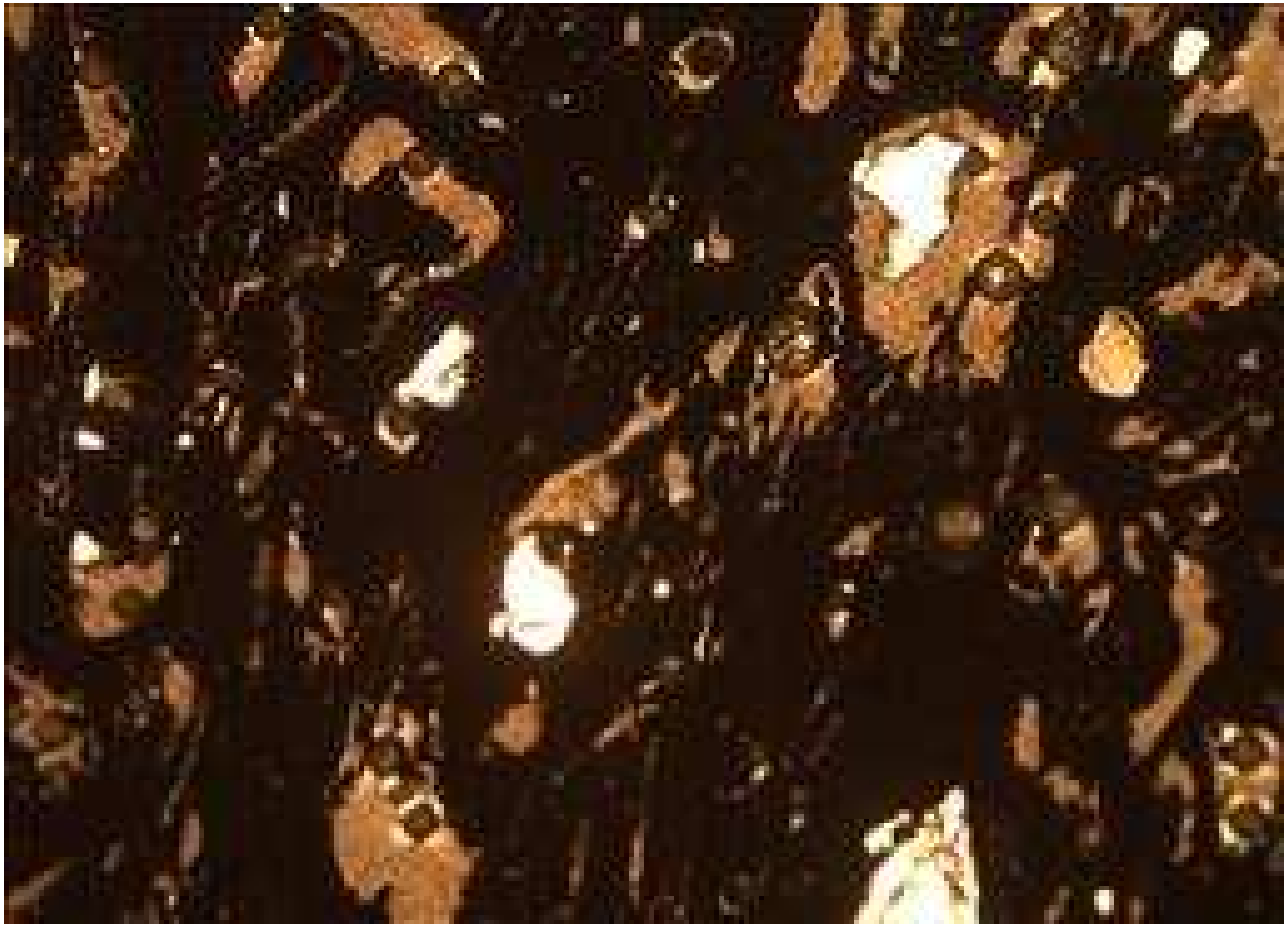


Bin Data

Bin	Length(µm) Lower	Length(µm) Upper	Count	Count1	Percent of Total Count
1	6.4	106.6	301	301	82.692
2	106.6	206.8	38	38	10.44
3	206.8	307.	14	14	3.846
4	307.	407.2	3	3	0.824
5	407.2	507.4	4	4	1.099
6	507.4	607.6	1	1	0.275
7	607.6	707.8	1	1	0.275
8	707.8	808.	2	2	0.549

SUR 20%

image0051.tif



Unenhanced image of the thin section. The small circular bubbles are a result of the epoxy used to make the thin sections.

SUR 20%

image0051.tif: Binary Mask

A binary mask is used to detect the pore spaces and allow the program to measure the longest dimension. The small circular bubbles are a result of the epoxy used to make the thin sections.

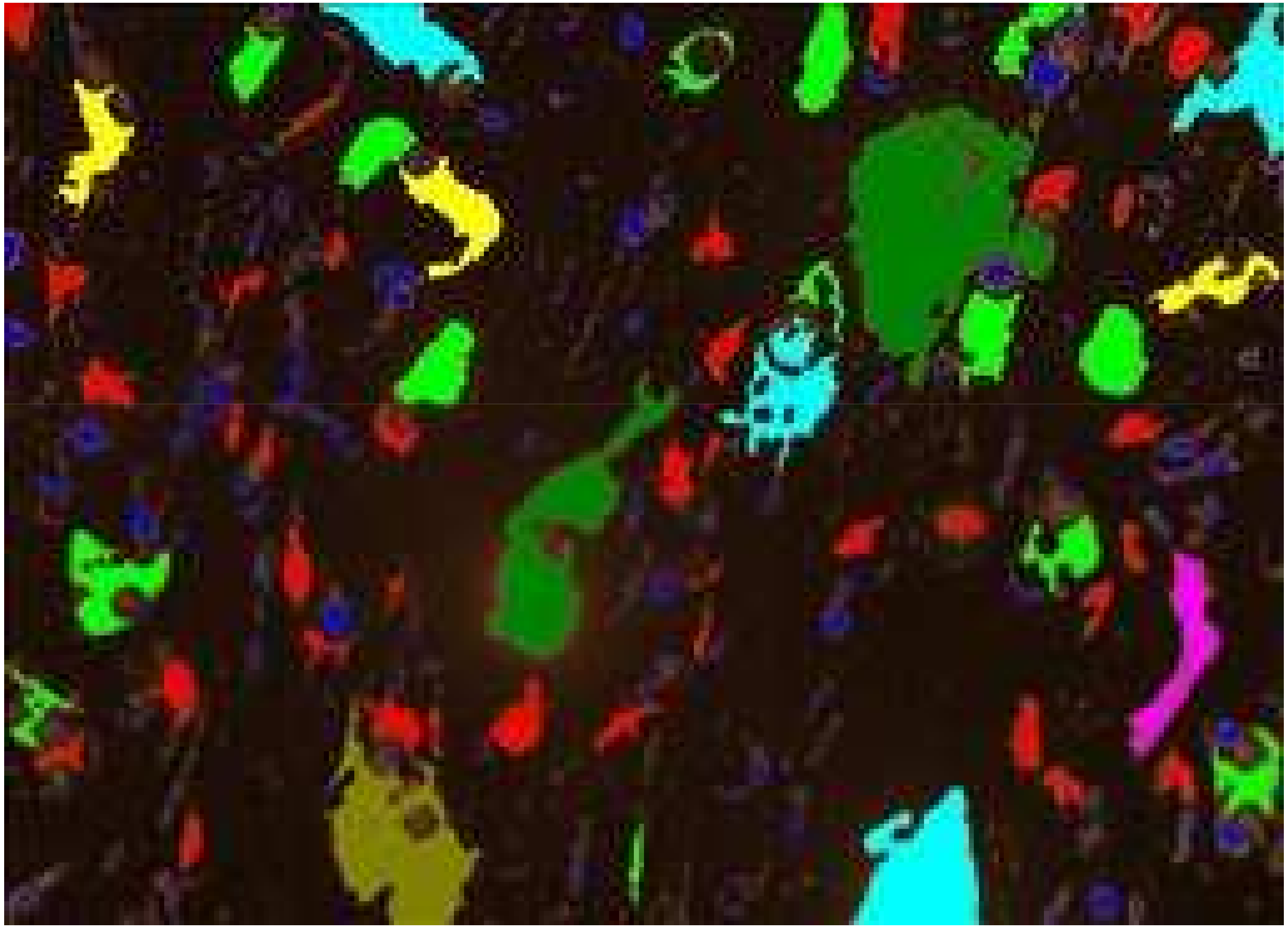
SUR 20%

image0051.tif: Labels

Measurements for the longest dimension of each of the pore spaces.

SUR 20%

image0051.tif: Colour Coded



Pore spaces are color coded based on size. Colors match the colors of the bins in the histogram.