Approaches in Drinking Water Provision in Developing Countries: An Investigation of Water Safety Plans and Ceramic Water Filters

A dissertation submitted by

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Abstract

Primarily, two interventions are advocated to address water safety concerns and work towards the Sustainable Development Goal (SDG) of populations drinking water from safely managed sources by 2030: Water Safety Plans (WSPs) and household water treatment (HWT). This dissertation investigated technologies associated with safe water provision at two scales: community (i.e. WSPs) and household (i.e. ceramic water filters).

First, a systematic review of WSPs was conducted to understand the current evidence and knowledge gaps in these implementations to better inform key stakeholders of research needs. Overall, 53 documents met inclusion criteria; evidence in support of financial and operational outcomes from WSP implementations was prevalent, but evidence on institutional and policy outcomes were lacking.

Second, a multi-country evaluation of rural, community-managed WSP implementations was conducted using a mixed methods protocol to evaluate how the WSP process was translated into these contexts and the functionality of the resulting implementations. In total, 817 household surveys, 1,113 water quality samples, and 256 focus groups and key informant interviews were completed. Overall, we found: 1) incomplete WSP implementations; 2) no documented microbiological water quality improvements in WSP-communities; and, 3) small water supply operations improvements. These results highlight the need for

complete WSP implementation with sufficient support, and question whether WSPs are the appropriate strategy for community-managed water systems.

Third, X-ray micro-computed tomography was used on ceramic water filters to characterize the pore network morphology of engineered pathways from four different filters. Results indicate 1) similarities in porosity (25-36%) and pore size distributions (mean pore radius 7.8-14.3 um) between filters manufactured under different parameters; 2) preferential alignment of pores normal to the direction of flow for rice husk pore-formers; and, 3) varying tortuosity factors (13.7-38.9) in a filter made with rice husk pore-formers as compared to tortuosity factors (3.8-5.2) in a filter made with sawdust when both filters have uniform porosity in the through-thickness direction.

To assure delivery of safe drinking water, a strategy integrating both intervention methods, WSP and HWT, would address safe water supply concerns across a broad spectrum. Further development and adaptation of these technologies is critical to achieving the SDGs.

This work is dedicated to my parents, Gregory and Gail String, who have epitomized the definition of hard work and perseverance.

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1 Introduction

1.1 Global water-related disease burden

Many people in developed nations take for granted reliable access to safe water; yet, according to the WHO/UNICEF Joint Monitoring Program, 663 million people were without improved sources of drinking water in 2015 (WHO and UNICEF 2015). The problem is exacerbated by the global trend towards urbanization that marginalizes the rural and peri-urban poor, resulting in a cycle of ill health and poverty within which children are typically the first to suffer from the burden of disease caused by dirty water and poor sanitation and hygiene.

According to the Bradley classification, water-related disease transmission includes waterborne diseases, water-washed diseases, water-based diseases, and water-related insect vectors (White, et. al., 1972). Classically defined transmission via the fecal-oral route can account for waterborne diseases and some water-washed diseases. Since the Bradley classification, research has shown that water-related disease transmission is more complicated when considering the impacts of source to point-of-use water quality deterioration, risks of fecal pollution, and chemical hazards. As such a proposal for a new classification has been suggested to include engineered water system diseases and to recast water-washed diseases as water-access-related diseases (Bartram and Hunter, 2015).

Water, sanitation, and hygiene (WASH) was estimated to have the potential to prevent at least 9.1% of the global disease burden and 6.3% of all deaths (Pruss-Ustun & Organization 2008). However, insufficient WASH accounts for 842,000 diarrheal deaths per year for low and middle income countries (Pruss-Ustun, 2014). In addition to diarrheal disease burdens, water-related illnesses as a result of chemical pollution or chemically contaminated groundwater, parasites, and insect vectored diseases cause chronic illness.

1.2 Global water safety and security

Globally, it was estimated that 1.8 billion people use a source of drinking water that contains fecal contamination, of which 1.1 billion consume from a source with >10 Escherichia coli (*E. coli*) or total thermotolerant coliforms (TTC), which is considered to pose at minimum a moderate health risk (Bain *et al.* 2014; World Health Organization 1997). Additionally, 884 million people lack a basic drinking-water service and 159 million people primarily rely on surface waters (WHO, 2017).

It has been reported that over the last 100 years the portion of the global population facing water scarcity increased from 14% to 58% as water consumption has increased 400% in the same time period (Kummu *et al.* 2016). The largest portion of the population now facing water scarcity is in developing countries, where rainfall seasonality, intermittent dry spells, drought years and high evaporation rates coincide with the regions experiencing the largest population growth (Rockström *et al.* 2007). Furthermore, it is estimated that by 2025 half of the world's population will be living in water-stressed areas (WHO, 2017).

As the world transitioned from the conclusion of the Millennium Development Goals to the beginning of the Sustainable Development Goals (SDGs), we were left with new targets for water and sanitation provision. Target 6.1 is to "By 2030, achieve universal and equitable access to safe and affordable drinking water for all" which will be monitored by indicator 6.1.1 "Percentage of population using safely managed drinking water services (UN Economic and Social Council 2015). A safely managed drinking-water service is defined as one that is available when needed, located on premise, and supplies contamination free water. As of 2015, globally 71% of people used a safely managed drinking water service meeting this definition (WHO, 2017).

Primarily, two interventions are advocated to address water safety concerns and work towards the SDG goal: water safety plans and household water treatment and safe storage.

1.3 Water Safety Plans

Water Safety Plans (WSPs) are the internationally recommended, comprehensive risk assessment and management tool designed to ensure the safety of drinking water (World Health Organization 2011). WSPs have been promoted since the 2004 launch of the World Health Organization's (WHO) Guidelines for Drinking Water Quality and the International Water Association's Bonn Charter for Safe Drinking Water (Breach 2012). A WSP implementation consists of five specific steps: 1) Preparation; 2) System Assessment; 3) Monitoring; 4) Management and Communication; and, 5) Feedback and Improvement (Bartram *et al.* 2009). To date, WSP processes have been implemented in over 90 countries and incorporated into policy or regulation in more than 60 countries (World Health Organization 2017).

Despite the widespread implementation and policy presence of WSPs, it has been noted that there is: 1) a lack of standardized methods for evaluating WSPs; and, 2) few evaluations have been completed (World Health Organization & International Water Association 2015; World Health Organization 2011).

Implementation of WSPs in rural, community-managed water supply systems present challenges as supplies may consist of a mix of public/private, intermittent, distributed/point sources. Additionally, the burden of maintaining the WSP often falls to a volunteer committee in the community that may not have access to resources sufficient for undertaking a WSP. Guidance manuals have been developed to simplify and tailor WSPs for maintainers of community-managed water supplies (Espinoza *et al.* 2009; Greaves & Simmons 2011; Mudaliar *et al.* ; Rickert *et al.* 2014; UNICEF & Global Water Partnership 2014; World Health Organization 2012). Current evidence on WSPs in community-managed, rural supplies is limited, with lessons from four identified cases studies suggesting: 1) to rely on minimal water quality testing in favor of sanitary inspections for hazard identification and implementation of control measures (Barrington *et al.* 2013; Hasan *et al.* 2011; Mahmud *et al.* 2007); 2) need for organizations to use interactive workshops and tools; and, 3) to couple WSP implementations with existing WASH education activities (Barrington *et al.* 2013; Hasan *et al.* 2011; Mahmud *et al.* 2007; Timilsina 2012). However, as case studies are highly tailored to local context, it is difficult to ascertain what lessons are globally scalable and identifies an evidence gap.

The focus on safe management of drinking water increases the emphasis on the role of household water treatment (HWT) products in the short and medium term, while risk management strategies for water supplies, such as WSPs, are implemented in the long-term.

1.4 Household water treatment and safe storage

HWT is a type of point-of-use intervention, where the consumer assumes responsibility for treatment of their own water supply. Effective, accessible, and correctly, consistently, and continually used HWT technologies reduce diarrheal disease by improving the microbiological quality of water (Clasen & Menon 2007; Clasen *et al.* 2015; Fewtrell *et al.* 2005; Waddington *et al.* 2009; Wolf *et al.* 2014).

In 2014 WHO established the ‘International Scheme to Evaluate Household Water Treatment Technologies’ to globally evaluate the microbiological performance of HWT products (World Health Organization 2016). The Scheme provides clear performance targets and independent evaluation of products to 1) provide information to aid stakeholders in making informed choices about the products they are implementing; 2) highlight the need for strengthening regulation from national governments; and, 3) strengthening the quality of locally manufactured products. In Round I of testing of the scheme, one ceramic pot water filter was evaluated (World Health Organization 2016). Results highlighted the continued need to understand manufacturing variants affecting the performance of ceramic filters, which had previously been noted in an aggregation of best practices by the Ceramics Manufacturing Working Group (The Ceramics Manufacturing Working 2011).

1.5 Ceramic Pot Water Filters

Ceramic pot water filters are locally manufactured by organizations of varying production capacities around the world (The Ceramics Manufacturing Working 2011). The filters are produced by mixing a burn-out material, such as rice husk, sawdust, or other similarly organic material, with locally available clay, which are pressed into shape and fired to ceramic. On average a filtering element is designed to filter 1-3 L of water per hour when fully saturated.

Because ceramic pot filters rely on the physical removal of contaminants via pore size exclusion and adsorption, they are quite effective against the removal of bacteria and protozoa (World Health Organization 2016). Many studies, in both the field and laboratory, have been conducted on the microbiological effectiveness of ceramic pot filters; filters have been shown to be effective at removing 90-99.99% of bacterial organisms (Brown & Sobsey 2006; Johnson *et al.* 2008; Brown

2007) and improving water to the WHO "low-risk" classification of <10 *E. coli* per 100 mL (Johnson *et al.* 2008; Brown 2007; Roberts 2004; WHO 1997). They have also demonstrated >99% removal of protozoan (Lantagne 2001; van Halem *et al.* 2007).

The flow rate of the filters is predominantly affected by filter morphology, which is primarily determined by type and size of burn-out material, type of clay, and the ratio of burn-out material to clay (Klarman 2009; Hagan *et al.* 2009; Oyanedel-Craver & Smith 2008; Rivera-Garza *et al.* 2000). Characterization of the pore network morphology is possible using x-ray computed tomography (CT).

Micro-CT is a non-invasive imaging technique effective at differentiating the internal composition of samples by taking advantage of a material's x-ray attenuation coefficient (Henke 2017). The x-ray attenuation coefficient of a material is dependent on the it's density, atomic number, and the x-ray photon energy of the source (Jackson & Hawkes 1980; Heismann *et al.* 2003). CT scans are reconstructed into 3D image volumes and subsequently analyzed to provide information on the pore network and ultimately the manufacture of ceramic filters.

1.6 Research Objectives

The work presented herein responds to a call for improved understanding of technologies associated with two approaches to ensuring water safety: risk assessment and management of the supply and household water treatment. To achieve this research objective, three separate research projects were conducted as follows:

Chapter 2: A systematic review of outcomes and lessons learned from general, rural, and country-specific Water Safety Plan implementations (literature review)

Chapter 3: Operational research on rural water safety plans: case study results from implementations in India, DRC, Fiji, and Vanuatu (field evaluations)

Chapter 4: Investigation of the pore network morphology of ceramic water filters (laboratory evaluation)

While Chapters 2 and 3 investigate the larger framework of ensuring drinking-water of safe quality is delivered to consumers, Chapter 4 develops a method for the characterization of the filtration networks of an end-user HWT product option.

2 A systematic review of outcomes and lessons learned from general, rural, and country-specific Water Safety Plan implementations

2.1 Abstract

Water Safety Plans (WSPs) are a comprehensive risk assessment and management approach to water delivery that were internationally recommended in 2004. WSPs consist of five implementation steps, followed by evaluation. To date, approximately 90 countries have implemented WSPs, however widespread uptake is limited by lack of documented outcomes and impacts. We conducted a systematic review to collate outcomes, impacts, and lessons learned from WSPs developed in general, rural, and three case-study country contexts. Overall, 53 documents met inclusion criteria. In general contexts, the need for institutional support during WSP implementation was highlighted. In rural applications, the need to simplify the WSP process and provide community support was emphasized. In case study countries, we found the WSP process was selectively adapted and integrated within existing programs. In outcome and impact evaluations, financial outcomes have the clearest evidence base, while operational outcomes are documented most frequently, particularly in relation to infrastructure improvements. However, evidence is lacking on institutional and policy outcomes and impacts of WSPs. To ensure WSPs reach their potential for improving water delivery and management, support should be provided to implementers, outcomes and impacts of urban, peri-urban, and rural WSP implementations should be evaluated, and adaptation of WSPs locally encouraged.

2.2 Introduction

The goal of Water Safety Plans (WSP) is to ensure drinking water safety by preventing or minimizing contamination. WSPs were laid out in the joint 2004 launch of the 3rd edition of the World Health Organization's (WHO) Guidelines for Drinking Water Quality (World Health Organization 2011) and the International Water Association's (IWA) Bonn Charter for Safe Drinking Water (Breach 2012). They have their roots in risk management practices such as the multiple barrier approach and Hazard Analysis and Critical Control Points (HACCP), applied in the food industry, and balance the effort of stakeholders involved in water supply between testing of point-of-use water quality and risk assessment / management of the supply. Uptake of WSPs has resulted in implementations in approximately 90 countries, with policy or regulation development in more than 60 countries globally (World Health Organization & International Water Association 2015)

The WHO Guidelines state "the most effective means of consistently ensuring the safety of a drinking-water supply is through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer. In these Guidelines, such approaches are called water safety plans" (World Health Organization 2011). Similarly, the Bonn Charter states its primary goal is the provision of "good safe drinking water, which has the trust of consumers", and at the heart of this charter is the call for a risk based WSP from catchment to consumer (Breach 2012).

While the primary goal of a WSP is to protect public health, potential additional WSP benefits include: improved compliance with regulatory and other requirements; improved consumer trust;

improved confidence of key stakeholders; cost effectiveness and investment planning; improved staff commitment; and pricing competition with peers (Breach 2012).

The five key steps in developing a WSP are: 1) Preparation; 2) System Assessment; 3) Monitoring; 4) Management and Communication; and 5) Feedback and Improvement (Bartram *et al.* 2009). Two different models of WSP implementation exist, the full process comprised of 11 modules and the process for small systems comprising six tasks (Figure 2-1).

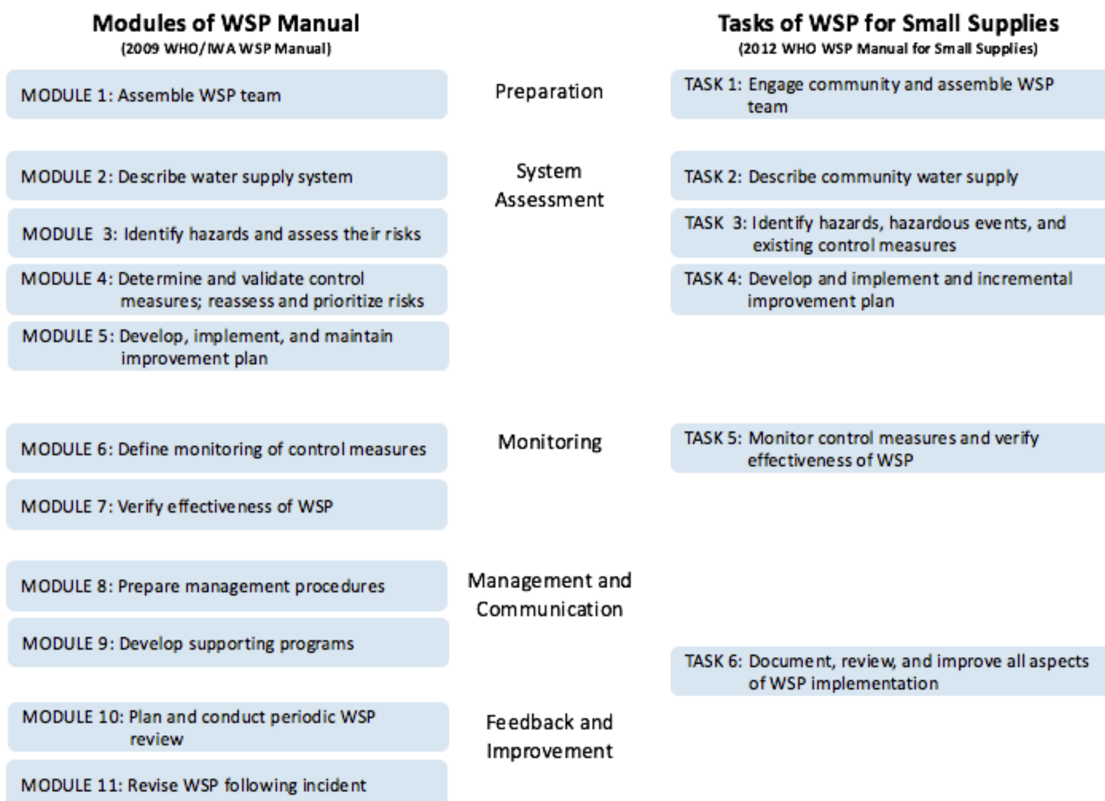

Figure 2-1: Steps of the WSP process and the associated modules and tasks (Bartram *et al.* 2009) and (World Health Organization 2012)

While validation and verification of the WSP occur in Steps 2 and 3 of the process (Mudaliar 2012) outcome and impact evaluation of a WSP is a separate, external activity to determine the overall outcomes and impacts of the WSP on the water supply chain. To date, outcome and impact evaluation of WSP implementation is lacking, which leads to stakeholder uncertainty in the value of developing and utilizing a WSP; however, a framework has been suggested by the CDC and to date larger scale evaluations have been planned by WHO (Aquaya 2015; Gelting *et al.* 2012; Williams 2008).

Additionally, rural communities present a special challenge to WSP development, as there may not be a primary water utility managing the supply, the supply may be intermittent or from sources lacking infrastructure, and capacity for water quality monitoring may be low (Rickert *et al.* 2014; World Health Organization 2012). WHO has noted there are knowledge gaps in the use and implementation of WSPs in rural settings and, in particular, community managed supplies (World Health Organization 2012).

As part of a United Nations Children's Fund (UNICEF) – Tufts University WSP project, we conducted a systematic literature review on WSPs in general contexts, rural implementations, and in three countries/areas of interest to the project: India, the Democratic Republic of the Congo (DRC), and the Pacific Islands, specifically Fiji/Vanuatu. The goal of this systematic review was to collate outcomes and impacts from WSP evaluations and lessons learned from WSP implementations in general, rural, and country-specific context.

2.3 Methods

Documents were gathered via database searching, utilizing PubMed, Engineering Village, and Google Scholar. Key search phrases included: "water safety plans", "water utility management", "water utility risk management", "rural water supply risk management", "evaluation of risk management water supply", "water risk management policy", and "evaluation water safety plan." Due to the size of the Google Scholar database, further down selection was conducted during the search, including limiting years of document publication to 1995-2015 and controlling specifically for the phrase "water safety plan." Additionally, the IWA/WHO Water Safety Portal was manually searched for documents and manuals, and publications were solicited directly from personal connections and the Household Water Treatment Google Group. Secondary literature searches were conducted by reference tracing in the identified literature. Lastly, UNICEF staff and local partners in the three focus countries provided information and documentation relevant to their country context.

The down selection process for documents returned from all search venues involved first evaluating the titles of potential papers, then reading abstracts, and finally reading full-text of selected papers. At each stage, documents were evaluated based on the inclusion and exclusion criteria (Table 2-1).

Table 2-1: Inclusion and exclusion criteria used to identify relevant WSP documents

Inclusion Criteria	**Exclusion Criteria**
Language: English, French, Spanish	Language: any language other than English, French, or Spanish
Publication: 1995-Nov 1, 2015	Publication: pre 1995
General WSP manuals/guidelines or associated guideline for implementation or evaluation	Specific WSP manuals/guidelines developed for non-generalizable situations (i.e. WSP in Buildings Manual, country specific policies)
Case studies of WSP implementation in general or rural setting with documented outcomes	Case studies which presented no outcomes, no clear examples indicating WSP process was followed, or a lack of information to draw conclusions
Any document pertaining to WSPs in countries of interest secured by UNICEF	Documents that were partial examples of a WSP, were Powerpoint presentations lacking detailed information, or were summaries of already published manuals

In full text review of down selected documents, documents including lessons learned or evaluation outcomes and impacts were identified, grouped into four categories, and analyzed. The four groups included 1) all studies for general context lessons learned (further sub-grouped into the five steps of WSP implementation); 2) lessons learned from rural contexts; 3) lessons learned from case study countries; and 4) outcomes and impacts from evaluations of WSPs. Documents could be included in more than one group.

2.4 Overall Results

Key phrase searching of PubMed garnered 608 possible documents, of which 76 met the inclusion criteria, while the Engineering Village database had 8,646 hits, of which 114 met inclusion criteria. Google Scholar searching identified 1,330 documents that met the inclusion criteria after the more stringent search parameters were included. Of the documents on the IWA Water Safety Portal, 108 were identified that met inclusion criteria. Three documents were included from reference linking. In total, 1,627 documents met inclusion criteria. After full-text reviews, 53 documents were included, of which: 12 were included for general WSP lessons learned; 12 were pertinent to the rural implementation context; 11 pertained to WSPs in case study countries; and 24 contained evaluation outcomes and impacts (Table 2-2).

2.5 Lessons Learned from General WSP Implementations

Of the 12 documents that generated general WSP lessons learned, six provided lessons for Step 1: Preparation, three for Step 2: System Assessment, three for Step 3: Monitoring, eight for Step 4: Management and Communication, and four for Step 5: Feedback and Communication.

Table 2-2: List of documents included in review

Author	Date	Manual	General WSP Steps					Rural WSP	Case Study	Eval
			1	2	3	4	5			
Barrington et al.	2013							✓		
Bartram et al.	2009		✓	✓	✓	✓	✓			
Breach	2012	✓	✓							✓
Chandrapur	2015								✓	
Davison & Deere	2007									✓
de Souza et al.	2011					✓	✓			✓
Dyck et al.	2007									✓
Espinoza et. al.	2009	✓						✓		
ESR	Draft								✓	
Gelting et al.	2012									✓
No Golden	Draft								✓	
Greaves & Simmons	2011	✓						✓		
Gunnarsdottir et. al	2008									✓
Gunnarsdottir et al.	2012a									✓
Gunnarsdottir et al.	2012b									✓
Gunnarsdottir et al.	2015									✓
Hasan and Gerber	2010									✓
Hasan et al.	2011							✓		
Howard et al.	2005									✓
Hubbard et al.	2013		✓				✓			✓
IWA	2004	✓								
Jalba et al.	2010		✓							
Kabir & Gedam	2012								✓	
Keirle & Hayes	2007			✓						
Kooy & Bailey	2012								✓	
FMoWIE	2015	✓						✓		
Lockhart et al.	2014	✓								✓
Mahmud et al.	2007					✓		✓		✓
Mälzer	2010									✓
Mudaliar	2012									✓
Mudaliar et al.	n.d.	✓						✓	✓	
Nath	2013								✓	
NEERI	2013								✓	
Ncube & Pawandiwa	2013					✓				
Perrier et al.	2014							✓		

Author	Date	Manual	General WSP Steps					Rural WSP	Case Study	Eval
			1	2	3	4	5			
Rickert et al.	2014	✓						✓		
Rinehold et al.	2011		✓	✓	✓	✓	✓			✓
Rizak et al.	2003									✓
Saltori	2013								✓	
Singleton	2014								✓	
Smeets et al.	2010									✓
Summerill et al.	2010a		✓			✓				
Summerill et al.	2010b					✓				✓
Timilsina	2012							✓		
UNICEF & GWP	2014	✓						✓		
Vieira	2011									✓
WSP	2010								✓	
Williams	2008									✓
WHO	2011	✓								
WHO	2012	✓						✓		
WHO	2014									✓
WHO & IWA	2015									✓
Zimmer & Hinkfuss	2007					✓				

2.5.1 Step 1: Preparation

In order to successfully prepare for a WSP process, multiple documents highlighted the need to: 1) assemble a well-supported interagency team led by the water utility (Bartram *et al.* 2009; Breach 2012; Hubbard *et al.* 2013; Rinehold *et al.* 2011; Summerill *et al.* 2010a); and 2) include the public health department in the process (Hubbard *et al.* 2013; Jalba *et al.* 2010; Summerill *et al.* 2010a).

Additionally, authors noted that carefully choosing the WSP coordinator, valuing the opinion of WSP team members with fresh perspectives (Bartram *et al.* 2009), having a team committed to long-term implementation of the WSP (Rinehold *et al.* 2011)and, recognizing a WSP's value as a capital improvement-planning and money-saving tool (Bartram *et al.* 2009; Rinehold *et al.* 2011) led to successful WSP planning.

2.5.2 Step 2: System Assessment

The process of assessing a water supply system encompasses Modules 2-5 or Tasks 2-4, including describing the water supply system, identifying hazards and hazardous events and their associated risks, determining and validating control measures, prioritizing risks, and developing, implementing, and maintaining an improvement or upgrade plan.

Keirle and Hayes called for broader stakeholder involvement in water supply after identifying that the catchment area is often beyond the jurisdiction of water companies in England and Wales (Keirle & Hayes 2007).

Bartram et al. noted through several case studies that utilizing existing data to determine the current water quality was critical to establishing discrepancies in perceived and actual quality, leading to better established control measures (Bartram *et al.* 2009). They also noted the importance of reaching agreement upon which water quality standards to use for validation of control measures and that validation of each control measure was required unless there was a confirmed robustness of existing data on certain controls. Furthermore, the importance of including hazards that occur on the consumers' premise in the risk assessment was documented.

Rinehold et al. corroborates this by noting point-of-use assessment is needed, in addition to testing of the quality of the supply, for consumers that store and treat water at home (Rinehold *et al.* 2011). Rinehold et al. further noted that the water quality standards should be clearly defined and locally appropriate, and in some cases a qualitative approach to prioritizing risks should be considered.

2.5.3 Step 3: Monitoring

Monitoring includes both defining the operational monitoring of the control measures outlined in Step 2 and verification that those measures continue to be both functional and relevant, through an audit or assessment. Monitoring parameters chosen for a particular WSP will be dependent upon: existing regulations, the availability of test equipment and expertise, the type of supply system, and the financial cost of utilizing a measure.

Bartram et al. noted that monitoring is an integral part of the WSP approach as it informs whether public health goals are being met (Bartram *et al.* 2009). They further observed a benefit that clearly defined operational monitoring plans helped to eliminate conducting irrelevant tests. Rinehold et al. noted monitoring not only ensures compliance but also offers a basis for identifying needed improvements (Rinehold *et al.* 2011). Furthermore, they observed that monitoring water quality can be difficult in resource-constrained systems, and this step of WSP implementation can be used to strengthen monitoring and improve water safety.

To aid the WSP community in verification of WSP effectiveness, the WHO and IWA published a practical guide to auditing WSPs (World Health Organization & International Water Association 2015). Divided into four audit categories, internal or external and formal or informal, the guide contains suggestions for why each type of audit would be performed and who would conduct it. The goal of a WSP audit, ideally carried out independent of the WSP team, is to provide feedback on WSP implementation and maintenance; provide a critical assessment of the effectiveness of the WSP; and, confirm compliance of the WSP with any regulation. Additionally, the guidelines call for the development of training tools and certification processes for auditors. Ultimately, the results of an audit, in conjunction with regular review of the WSP by the implementer, help to inform and strengthen the overall WSP process.

Bartram et al. observed that informal audits conducted in one case study helped to identify lapses in both data collection of monitoring parameters and in dissemination of information to key stakeholders(Bartram *et al.* 2009). In another case study they noted that the regulator, acting as an external auditor, planned to audit certain components of a WSP regularly for compliance and the WSP in its entirety on occasion.

2.5.4 Step 4: Management and Communication

The management and communication step of the WSP process calls for the development of a Standard Operating Procedure for the water supply system as well as the development of support programs and such as staff trainings and preventative maintenance.

Summerill et al. recognized that organizational culture has an influence on the effectiveness of WSP implementation and that leaders are key in not only developing this mindset but also in challenging the beliefs and attitudes of staff (Summerill *et al.* 2010b). Zimmer and Hinkfuss noted resistance to implementing WSPs may result from uncertainty and misconceptions surrounding the process (Zimmer & Hinkfuss 2007). Yet others acknowledged when staff are encouraged to collaborate they have been found to share their knowledge with each other and with colleagues not on the WSP team (Mahmud *et al.* 2007; Ncube & Pawandiwa 2013).

Several authors noted the importance of the WSP team having adequate experience and expertise in communication (Bartram *et al.* 2009; de Souza *et al.* 2011), while Rinehold et al. highlighted the need for thorough operator training (Rinehold *et al.* 2011). Proper training allows a team to prioritize and put in place an improvement plan when significant risks are identified, which helps a team avoid complacency and neglect of long-term safety improvements (Bartram *et al.* 2009; Summerill *et al.* 2010a).

2.5.5 Step 5: Feedback and Improvement

In addition to regular monitoring of the system, the WSP needs long-term feedback and continual improvement via reviews and assessments by the WSP team because of the iterative nature of the process.

Rinehold et al. indicated the WSP implementation team needs to determine how WSP success will be measured and what metrics will be used to evaluate it, while Bartram et al. noted it is imperative the assessment methodology be clear to allow for consistency (Bartram *et al.* 2009; Rinehold *et al.* 2011). Hubbard et al. noted that an infrequent reliance on benchmarks and indicators to monitor improvements and provide valuation is a hindrance to scaling up of WSPs (Hubbard *et al.* 2013). Bartram et al. also documented that paper based WSPs were difficult to keep updated as improvements to the system were implemented, and found in another case utilities maintaining WSPs on an intranet with version-control allowed for faster updating (Bartram *et al.* 2009). Furthermore, they observed from case studies that a well-defined plan for responding to different types of incidents allowed teams to respond quickly and provided a process for WSP revision if necessary.

The conclusions drawn from lessons pertaining to each step of the WSP process highlight the need for institutional support and collaboration, clear communication of goals, knowledge, and data amongst WSP implementers, and well thought-out organization of the WSP team in order to accomplish WSP implementation and upkeep. While many conclusions drawn relate to organizational culture of the WSP team and development of the WSP document, there are also important conclusions that can be made around the choice of indicators for system assessment, monitoring, and auditing.

2.6 Lessons Learned from Rural WSP Implementations

Several guidance manuals have adapted WSPs to community-managed water supplies, such as those found in rural settings (Espinoza *et al.* 2009; Greaves & Simmons 2011; Rickert *et al.* 2014; UNICEF & Global Water Partnership 2014; World Health Organization 2012) (Federal Ministry of Water Irrigation and Energy of Ethiopia 2015; Mudaliar *et al.*). WHO modified the eleven Modules to six Tasks and provided example programming geared towards professionals working towards implementation of WSPs in small communities (World Health Organization 2012). This document was expanded upon in 2014 to include simplified templates and guidance for community members introducing WSPs in community-managed supplies (Rickert *et al.* 2014). Implementers in Honduras refocused WSP requirements for community management and simplified the language of standard WSP manuals to meet the needs of rural communities (Espinoza *et al.* 2009). Global Water Partnership and UNICEF modified the WSP for small communities to a WSP-Plus, which included sub-tasks to assess the risk of environmental and climate change hazards (UNICEF & Global Water Partnership 2014). The Ministry of Water, Irrigation, and the Environment in Ethiopia developed detailed guidelines for the implementation of Climate Resilient WSPs in community-managed supplies, tailored to existing community and local governance structures (Federal Ministry of Water Irrigation and Energy of Ethiopia 2015). The Drinking Water Safety Planning guide for Pacific Island countries provides guidance in navigating not only the creation of WSPs but also in establishing national support processes and frameworks for rural WSPs (Mudaliar *et al.*).

Four case studies provided insight into WSP implementation in rural community supplies. Early adopters of WSPs in rural water systems in Alberta, Canada found 'interpersonal relationships' and 'communication dynamics' between operators and community or provincial officials were managed more effectively by the WSP process (Perrier *et al.* 2014).

In a study on WSP implementation in remote regions in the Pacific Islands, it was suggested that trained local facilitators assume the role of monitoring in place of the national government. WSP simplification was needed and it was suggested that modified sanitary inspections and hydrogen sulfide presence/absence tests be used in place of more formal monitoring (Hasan *et al.* 2011). Barrington et al. corroborated the need for minimal water quality testing, a focus on hazard identification, and control measure implementation in a study on pilot WSP implementations in Nepal (Barrington *et al.* 2013). While Mahmud et al. found the use of sanitary inspections to be a useful indicator of improved source water condition, with a decrease from 8% to 1% of water sources in the high risk category and an increase from 69% to 89% of sources in the low risk category in pilot projects (Mahmud *et al.* 2007). In comparison, microbiological data indicated that 20% of supplies were reduced from a high or very high-risk rating.

Several authors also noted the need for interactive workshops and tools, such as flow diagram mapping, hazard identification, and the development of pictorial tools for community monitoring, coupled with water, sanitation, and hygiene (WASH) education in community-based management (Barrington *et al.* 2013; Hasan *et al.* 2011; Mahmud *et al.* 2007; Timilsina 2012). During microbiological testing, Mahmud et al. found 20% increase in household water samples in the low to no risk category and 15% decrease of household samples in the high to very high risk category after hygiene promotion under WSP pilot implementation (Mahmud *et al.* 2007).

2.7 Lessons Learned from Country Specific Case Study WSP Implementations

Twelve documents have described the state of WSPs in the four case study countries; five in India, two in the DRC, and four in the Pacific Islands.

2.7.1 India

In India, individual states develop water and sanitation service delivery strategies. A primary concern is water supply, with many states focusing on the development of Water Security Plans (WSePs) (National Environmental Engineering Research Institute 2013), as distinct from WSPs. The goal of a WSeP is to ensure that every rural person has enough safe water to meet their drinking, cooking, and domestic use needs at all times and in all situations.

UNICEF operates in 14 states in India, of which five have developed WSePs/WSPs for piloting (2015). One program that UNICEF has been involved with is the Bio Village Project in 110 villages (approx. 24,000 families) in Maharashtra to develop a Village Water Safety Security Plan (VWSS) (Kabir & Gedam 2012). The VWSS is divided into activities in support of source management, water system management, and water quality monitoring and surveillance. After a pilot period, it was found that: 85% of villages had conducted their own water supply repairs; nearly 100% had appointed a water manager and conducted operation and monitoring training; the water tax recovery rose in the first district by 28% and in the second district by 8%; 98% of villages were consistently chlorinating water supply; but, only 56% maintained regular logs. Key recommendations were made for taking this initiative to scale, including: 1) triggering community behavior change through participatory approaches; 2) obtaining external support, especially for the training and capacity building to the districts; and 3) developing process guidelines and appropriate tools for conducting Trainings of Trainers. VWSS Plans in Chandrapur District operate under a larger District WSP that provide a water quality monitoring framework, labs, and guidelines for infrastructure planning and funding allocation to villages (2015).

The Sulabh International Academy of Environmental Sanitation and Public Health (SIAES) and WHO India have developed specific guidelines for different types of water supply systems in India, which are integrated into broader Government of India guidelines on WSePs (Nath 2013). Additionally, the Water and Sanitation Program has produced a detailed report on policy issues related to implementation of WSPs in rural India (Water and Sanitation Program 2010). Key policy issues that have been identified are: adopting WSPs, establishing roles and responsibilities, demonstrating that WSPs are a basis for investment, setting performance targets to reflect health objectives, and developing policies on interventions. They also identified the need for reporting and auditing, district planning coordination, and baseline surveys of water quality as critical functions to support WSP implementation.

2.7.2 Democratic Republic of the Congo

The DRC government-operated national WASH development program, Village Assaini, was established in 2006 by the Ministry of Health and Ministry of Education to contribute to achieving the Millennium Development Goals, with a goal of reaching 2,850 villages and 1,000 schools by 2012. The primary support for the Village Assaini program came from UNICEF, with UNICEF acting as a trainer of public servants across the country and a supporter of NGOs to implement

WASH activities alongside government agencies in villages. They also provided institutional support of the National Water and Sanitation Committee, the Action on Water Supply and Sanitation, and the Provincial Department for Health by paying salaries, equipment, and administrative costs (Kooy & Bailey 2012).

The WSP process was integrated into the existing Village Assaini program through the Pas a Pas Manual, by evaluating overlap points between the two programs (Saltori 2013). As a result, only four new activities were added to the Village Assaini program: visit the water sources, develop WSP operation plans, develop an emergency-plan, and develop an auditing plan. A challenge in implementing WSPs in the DRC is the lack of capacity for water quality analysis, especially in the rural areas. Therefore, validation and verification of WSPs are based on proxy indicators of quality, like turbidity, experience with the water supply, and local knowledge of the source. In his report on the experience of introducing WSPs to the Village Assaini program, Saltori also developed KAP surveys and community worksheets for this context (Saltori 2013). The first Village Assaini communities with integrated WSPs are currently in pilot.

2.7.3 Pacific Islands

Water Safety and Security Planning has been actively pursued in the Pacific for a number of years, with development on several islands, including Fiji and Vanuatu. Management of freshwater supply in the Pacific is threatened by climate change, fragile groundwater supply, and remoteness of many islands. A lessons learned guide on setting up national support processes and implementing the WSP process was written to share pilot experiences in Tonga, Cook Islands, Palau, and Vanuatu (Mudaliar *et al.*). At a national level, in Tonga a new steering committee was elected to manage WSPs, whereas in Cook Islands and Vanuatu, old committees were renamed and tasked with developing safe drinking water programs. Part of the national strategy was to then develop legislation and policies on drinking water supply and create a coordination plan for sector actors.

In Kiribati, for instance, where there is a shallow freshwater lens in porous coral soil, the importance of sanitation cannot be overstressed. However, due to the fragility of the lens, traditional "improved" toilets can prove just as harmful as "unimproved" ones because of infiltration (In preparation). To combat these issues, a toolkit for WASH safety planning in schools has been developed, with an aim of broadening the risk assessment and management approach to better align a multitude of connected activities (Environmental Science and Research In preparation).

In Fiji, 15 communities have had WSPs implemented, with another 20 planned by the Ministry of Health in the coming year. In Vanuatu, 20 WSPs have been created with community implementation partners and the Department of Geology, Mining, and Water Resources. Further development in the Pacific has focused on the creation of monitoring and verification templates to be used by implementing partners in assessing the WSPs in communities. At this time, monitoring activities have been carried out in four communities in Fiji and have not been formalized in Vanuatu (Singleton 2014). Three of the four communities monitored were showing enough progress to advance further in their programs.

Overall, the key lesson from focus countries we investigated is that they have heavily modified WSPs by adopting them to the local context and integrating them into other existing programs. In India this included the national government allowing specific policy directives to be determined by each state based on local water quantity and quality issues. In the DRC, WSPs were integrated into a nationally supported and recognized community WASH program to avoid the creation of parallel structures. In the Pacific Islands, each country approached the process according to quality needs, some in the context of climate resilience, and according to local government structure.

2.8 Evidence for Evaluation Outcomes and Impacts

The need for evaluation of WSPs has been extensively noted. A significant issue observed at the 2008 Lisbon Water Safety Conference was the lack of an evidence base in support of WSPs (Williams 2008). Stemming from this conference was an increase in the call for health-based targets to be utilized as evidence in support of WSPs (Dyck *et al.* 2007). In Honduras, for instance, the efforts to integrate WSP methodology into national drinking-water legislation fell short when there was not enough evidence-base to support the health impact of a WSP (Hubbard *et al.* 2013). Davison and Deere, suggested that key public health indicators, when used in conjunction with operational targets, were a more comprehensive way of monitoring a water supply in Pacific Island Countries (Davison & Deere 2007). Vieira called for both global monitoring of WSP development and global benchmarking with utilities all utilizing the same set of tools and performance indicators (Vieira 2011).

The United States Centers for Disease Control and Prevention (CDC) developed a conceptual framework for WSP outcome and impact evaluation as a complement to other WSP implementation manuals (Gelting *et al.* 2012). The primary goal of the framework is to provide a common terminology for defining WSP outcomes and impacts and the indicators upon which they are measured to illustrate the benefits of WSP implementation and establish an evidence base for WSP effectiveness. To achieve these tasks, a logic model containing inputs (human, financial, organizational, and community resources), activities and outputs of WSP document creation, outcomes (institutional, operational, financial, and policy change and regulation), and impacts related to health, supply, and operational targets was utilized (Gelting *et al.* 2012)

Mudaliar argued that the CDC's conceptual framework did not provide direct evidence of WSP benefits, and further states that most WSP evaluation is focused on the stages of document development (Mudaliar 2012). He suggested the development and use of Key Performance Indicators to provide conclusive evidence of WSP effectiveness extended to water quality, operational performance, institutional performance, and to create separate indicators for small community-led supplies. Lockhart et al. operationalized the CDC's framework into 25 specific KPIs that can be used to evaluate a WSP across institutional, operational, financial, and policy change outcomes (Lockhart *et al.* 2014).

Only two studies set out to conduct an impact evaluation of Water Safety Plans (Gunnarsdottir *et al.* 2012a; Gunnarsdottir *et al.* 2012b). Thirteen other studies presented data associated with the implementation of WSPs . Although they were not conducted as impact evaluations, they presented evaluation outcomes and lessons learned, which we have arranged by the CDC's outcome indicators to present examples of the type of information that is currently available. Of these documents, three presented institutional lessons learned, eight presented operational lessons, two presented financial lessons, and five presented policy/regulation lessons. In the next section, we present these studies organized by outcome category and summarize the limited impact evaluation results (even if the studies themselves were published prior to development of the CDC's evaluation framework).

2.8.1 Institutional Outcomes

In lower income countries, the value of investing limited resources in a WSP may not be seen by water suppliers where day-to-day demand already exceeds both their personnel and fiscal capacities (Rinehold *et al.* 2011). Summerill noted the extensive influence of organizational culture on both the attitudes of the water utility staff and on the long-term commitment of the WSP team in implementation (Summerill *et al.* 2010b). Furthermore, Rizak et al. found management practices, such as communicating changes in water treatment, could have a positive effect on consumer satisfaction (Rizak *et al.* 2003).

2.8.2 Operational Outcomes

Infrastructure improvements after WSP implementation, such as source repair and decontamination, were noted in several case studies (Gelting *et al.* 2012; Howard *et al.* 2005; Mahmud *et al.* 2007).

Gunnarsdottir and Gissurarson evaluated ten years of Icelandic use of HACCP for water supplies (Gunnarsdóttir & Gissurarson 2008). They found an improvement from 88% to 99% water quality compliance in one city and 94% to 99% compliance in a second after the implementation of HACCP. These improvements came about after an initial documentation of corrective actions and system failures for each water supply was undertaken.

One follow-up study by Gunnarsdoittir et al. found that the WSP implementation process improved utility culture, but that lack of audits and communication with the public were still operational shortcomings of the process (Gunnarsdottir *et al.* 2012b). Another follow-up study by Gunnarsdoittir et al. that tracked water suppliers before and after WSP implementation, found detection of *E. coli* decreased from 1.28% to 0.32% after WSP implementation (Gunnarsdottir *et al.* 2012a).

Smeets et al. evaluated the use of quantitative microbial risk assessment (QMRA) in monitoring the safety of a water supply managed by a WSP; he utilized treatment data, estimated the number of failures, and tested treatment efficacy to determine the probability of detecting a failure event (Smeets *et al.* 2010). Factors that complicated this assessment included the occurrence of "special events" in 10% of datasets, such as when human error led to high chemical concentrations. A process-monitoring log was suggested for water suppliers to test water quality and an example of setting critical limits based on the QMRA model was developed.

A second study of microbial risk in a water supply managed by a WSP was conduced by de Souza et al. on a municipal water supply in South Africa, where the Department of Water Affairs introduced an incentive-based regulatory program and associated regulatory drinking water quality information system, to water suppliers in the country (de Souza *et al.* 2011). The electronic Water Quality Management System (eWQMS) platform allows municipalities to load drinking water quality data to a database and track the performance of key management functions and was integrated with additional information critical to successful operation of a supply via a WSP approach. While the WSP tool implemented in eWQMS is available to utilities in the system, it was found only 20% of systems assessed had a WSP in place.

2.8.3 Financial Outcomes

In Uganda, there was a 30% reduction in costs of water control activities when monitoring was done at intermittent points along the supply chain instead of only verifying the final product. This was attributed to earlier identification of problems in the supply (Howard *et al.* 2005). In Palau, Hasan and Gerber found that for every $1 USD invested in a WSP there was a $6 USD return on investment when comparing the capital cost of WSP investment to the long-term savings of reduced health costs, fewer purchases of water from other sources, and leakage reduction (Hasan & Gerber 2010).

2.8.4 Policy/Regulation Outcomes

Policy incentives alone may represent too large of a regulatory workload in countries that are already trying to enforce existing regulations, requiring a critical balance between top-down policy directives and bottom-up support of WSPs (Rinehold *et al.* 2011).

Several years ago, Germany adapted the WSP approach to fit into their technical guidelines to support water utilities' internal management schemes, particularly in for those without existing Technical Risk Management plans (Mälzer *et al.* 2010). The WHO noted extensive plans for policy and regulatory development from 2015-2020 in eastern European, Caucasus, and central Asian countries through the Protocol on Water and Health, although definitive policy documents are still in development for many countries (World Health Organization 2014).

An update to the study that evaluated the national framework for safe drinking water found that enforcement to regulation is particularly lacking, but mandatory requirements for WSPs have been beneficial for improving compliance to regulation (Gunnarsdottir *et al.* 2015).

2.8.5 Summary of Outcomes and Impacts

Overall, the outcomes of WSP implementation are still mixed and the dataset is weak; a stronger evidence base that tracks both the outcomes and impacts of WSP implementation is needed. From the case studies that were reviewed, it was found that financial outcome evaluations have been clearest, while the evidence from operational outcome evaluations that pertain to improvement of infrastructure have been stronger than those related to the improvement of procedures at water suppliers. Currently, there is a lot of promising development in policy outcomes, although follow-through on how policies are carried out and regulated is needed. The weakest evaluations to date have been for institutional outcomes.

Because the case studies were mostly limited in scope, the degree to which the observed outcomes of the WSPs are directly attributable to implementation of the WSPs is unknown. However, of the impacts noted in the framework, most outcomes may point to water supply improvements, as seen by results already noted elsewhere in this review (Gunnarsdottir *et al.* 2012a; Kabir & Gedam 2012; Mahmud *et al.* 2007). For example, Gunnarsdottir et al. noted that mean non-compliance to Icelandic Drinking Water Regulation decreased by 80% after WSP implementation. It was further documented that there was also a decrease in non-compliance in water sample collection at both the source and in the distribution network (Gunnarsdottir *et al.* 2012a).

Outcomes that may preliminarily point to health improvement impacts are extremely limited. Gunnarsdottir et al. found that both mean and median rates of diarrhea were statistically significantly lower and that the 95th percentile was reduced by half when WSPs were implemented than without a WSP (Gunnarsdottir *et al.* 2012a). They also documented a 14% reduction in incidence of diarrhea in areas with a WSP, but they did not find any statistically significant correlation between lower incidence and a utility scoring better on WSP implementation. While in a German hospital environment, Dyck et al. found that neonatal sepsis and hospital acquired infections were reduced after implementing a WSP (Dyck *et al.* 2007). These limited results point to the continued need for evidence based, documented impacts to both water supply and health after WSP implementation.

2.9 Discussion

Water Safety Plans are a comprehensive risk assessment and management approach to water delivery. The goal of this review was to collate lessons learned and evaluation results by general contexts, rural implementations, and focus country case studies. Of the 53 documents included in this review, 12 were included for general WSP lessons learned; 12 were pertinent to the rural implementation context; 11 pertained to WSPs in case study countries; and 24 contained information related to evaluation of outcomes and impacts. In general lessons learned, a majority of studies provided qualitative insight, but it is seen from the evaluations that there is a disparity in the number of studies that have actually conducted an impact assessment. This highlights the need for continued operationalization of the framework for evaluation to build the evidence base for WSP usage. From rural context applications, we have seen the need to modify the WSP framework and provide support to community managed supplies. It is apparent from lessons learned on the case study countries that stakeholders need to adapt the WSP to their local context. Overall, we found three themes in the lessons learned identified in this paper: 1) support; 2) need for evaluation of outcomes and impacts; and, 3) adaptation.

Support for WSP implementation could not be overstated. The need for external WSP expertise was highlighted frequently in the steps of implementation, particularly in Step 1 when assembling the WSP team and stakeholders (Bartram *et al.* 2009; Howard *et al.* 2005; Summerill *et al.* 2010a). Case studies on WSP implementation demonstrated the importance of support from implementing partners external to the water supplier, such as the government, interagency committees, or NGOs (Bartram *et al.* 2009; Breach 2012; Gunnarsdóttir & Gissurarson 2008; Jalba *et al.* 2010; Kabir & Gedam 2012; Kooy & Bailey 2012; Rinehold *et al.* 2011). It was also noted that there is a lack of practical tools for education, surveillance, monitoring, and research to support implementation (de

Souza *et al.* 2011; Hubbard *et al.* 2013). Continued support of WSPs through further publication of case studies, lessons learned documents, and manuals/guidelines will help to drive the conversation around implementation forward.

In general, outcome and impact evaluation data demonstrating WSP value remains weak. The new CDC framework for evaluation has provided common metrics against which to assess WSP across institutional, operational, financial, and policy outcomes and the impact categories of improvements in water supply and health. Of the weak evidence base, evidence on financial outcomes of WSPs is the clearest, with evidence that a WSP provides fiscal value to water suppliers and consumers (Hasan & Gerber 2010; Howard *et al.* 2005). The largest body of evaluation evidence of WSPs is on operational outcomes, however, results remain mixed as evidence of procedural improvement is weaker than that in support of infrastructure improvements (de Souza *et al.* 2011; Gelting *et al.* 2012; Gunnarsdóttir & Gissurarson 2008; Mahmud *et al.* 2007; Rizak *et al.* 2003; Smeets *et al.* 2010). Evidence on institutional outcomes are varied, with stronger evidence in relation to organizational culture of the WSP team, but weaker evidence in relation to long-term activities of the team (Bartram *et al.* 2009; Hubbard *et al.* 2013; Rinehold *et al.* 2011; Summerill *et al.* 2010a; Zimmer & Hinkfuss 2007). To date policy outcomes have a lesser evidence base despite clear momentum, which could simply be due to the fact that policies and regulations have not yet been documented on a global scale. Lastly, there is minimal evidence from impact evaluations of WSPs, with indications that there may be more documented in relation to water supply improvements, but only preliminary data on health improvements. At this time, the rigorousness of studies does not yet support drawing clear links from outcomes of WSPs to attributable impacts.

WSP adaptation has been highlighted particularly in relation to small community-managed supplies, like those found predominantly in rural areas (Espinoza *et al.* 2009; UNICEF & Global Water Partnership 2014; World Health Organization 2012). Adaptation to the local context provides implementers with language and monitoring techniques common to their experience (Espinoza *et al.* 2009; Hasan *et al.* 2011). WSP modification, as seen in India with the implementation of VWSS and WSePs, leads to plans that are more aligned to the existing requirements of local government agencies in regards to water delivery (Kabir & Gedam 2012; Water and Sanitation Program 2010). Furthermore, adaptation of WSPs to integrate with existing programs, such as the incorporation with Village Assaini in the DRC, can lead to a more streamlined implementation and less overhead work by stakeholders (Kooy & Bailey 2012; Saltori 2013).

The limitations of this study included: securing documents that pertain to case study WSP implementations that were not published, limiting the inclusion language to English, French, and Spanish, and securing documents that pertained to work in the case study countries of interest to the UNICEF program.

Further research is needed on the evaluation of outcomes and impacts of WSP implementations and on WSP implementations in rural communities. There is active, ongoing work to address both of these topics. The UNICEF work that motivated this review will attempt to provide more insight into documenting rural WSP implementations by assessing pilot programs over the next two years. A recent call for proposals to conduct evaluations in 10 countries by WHO highlights their interest in pursuing WSP evaluation metrics and in building an evidence base for WSP usage (Aquaya 2015).

2.10 Conclusions

WSPs have shown promise not only a risk mitigation tool, but also as a cost effective venture for water suppliers, despite challenges in on the ground implementation. To ensure WSPs reach their potential for improving water delivery and management, this review found: 1) support should be provided to implementers; 2) outcomes and impacts of urban, peri-urban, and rural WSP implementations should be evaluated; and, 3) local adaptation of WSPs encouraged.

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3 Operational research on rural, community-managed Water Safety Plans: case study results from implementations in India, DRC, Fiji, and Vanuatu

3.1 Abstract

Water Safety Plans (WSPs) are internationally recommended risk assessment and management strategies for water delivery. However, documented outcomes and impacts from implementing WSPs are lacking, particularly for community-managed supplies. In this research, community-managed WSP implementations in four countries were evaluated through a mixed-methods protocol of WSP implementation quality assessment, household surveys, source and stored household water quality sampling, key informant interviews (KII), and focus group discussions (FGD). Overall, 817 household surveys, 1,113 water quality samples, and 256 KIIs and FGDs were completed. WSP implementation quality was assessed at 6-13/18 points. Control village households reported paying for water less than WSP in DRC and Vanuatu ($p<0.001$). WSP village water sources had more *E. coli* contamination than control village sources in DRC ($p=0.009$), Fiji ($p=0.020$), and Vanuatu ($p=0.004$); household results varied. KIIs and FGDs found WSP communities had improved capacity to manage water supplies and identify key risks to safe water delivery. Overall, we found: 1) incomplete WSP implementations; 2) no documented microbiological water quality improvements from WSPs; and, 3) small water supply operations improvements. These results highlight that WSPs should be completely implemented with sufficient support for communities, and question whether WSPs are the appropriate strategy for community-managed water systems.

3.2 Introduction

Water Safety Plans (WSPs) are a comprehensive source to point-of-consumption risk assessment and management tool designed to ensure the safety of drinking water (World Health Organization 2011). WSPs have been promoted since the 2004 launch of the World Health Organization's (WHO) Guidelines for Drinking Water Quality and the International Water Association's Bonn Charter for Safe Drinking Water (Breach 2012). A WSP consists of five specific steps – Preparation, System Assessment, Monitoring, Management and Communication, and Feedback and Improvement – with associated sub-module(s) (11 in total) that provide guidance and structure to the process (Bartram *et al.* 2009). To date, WSPs have been implemented in >90 countries and integrated into policy or regulation in >60 countries (World Health Organization 2017). WSP principals are incorporated into the new Sustainable Development Goals, as the proposed metric for drinking water is "percentage of population using safely managed drinking water services" (Statistical Commission 47th Session of UN ECOSOC 2016).

Despite the widespread implementation and policy presence of WSPs, there is: 1) a lack of standardized methods for evaluating WSPs, despite recent auditing guidelines; and, 2) few evaluations have been completed (World Health Organization & International Water Association 2015; World Health Organization 2011). The Centers for Disease Control and Prevention developed a framework for assessing WSP implementations in four outcomes areas – institutional, operational, financial, and policy change and regulation – from which key performance indicators were developed (Gelting *et al.* 2012; Lockhart *et al.* 2014; Mudaliar 2012). A review of available evidence across these outcome areas found: 1) financial outcomes have the clearest evidence base in case studies; 2) operational outcomes, particularly in relation to infrastructure improvements, were documented most frequently; 3) despite the prevalence of policy/regulation and ad hoc knowledge of institutional change, those outcomes had the least evidence in literature (String & Lantagne 2016). Recent evidence has found developed-nation water suppliers with documented improvements in water quality and related operational parameters after WSP implementation and external institutional support for WSPs is critical to meet outcome goals (Gunnarsdottir *et al.* 2012a; Rinehold *et al.* 2011; Setty *et al.* 2017; World Health Organization 2017).

Rural, community-managed water supply systems are different than large, urban systems as they typically consist of non-centralized, possibly intermittent, point sources. Guidance manuals have been developed to simplify and tailor WSPs for community-managed water suppliers by reducing the 11 sub-modules to 6 suggested tasks (Espinoza *et al.* 2009; Greaves & Simmons 2011; Mudaliar *et al.* ; Rickert *et al.* 2014; UNICEF & Global Water Partnership 2014; World Health Organization 2012). The evidence on WSPs in these settings is limited, with lessons from four identified case studies suggesting: 1) to rely on minimal water quality testing in favor of sanitary inspections for hazard identification and implementation of control measures (Barrington *et al.* 2013; Hasan *et al.* 2011; Mahmud *et al.* 2007); 2) the need for interactive workshops and tools (Barrington *et al.* 2013; Diamond 2000; Hasan *et al.* 2011; Mahmud *et al.* 2007; Timilsina 2012); and, 3) to couple WSP implementations with existing water, sanitation, and hygiene (WASH) education activities (Barrington *et al.* 2013; Diamond 2000; Hasan *et al.* 2011; Mahmud *et al.* 2007; Timilsina 2012). However, as case studies are tailored to local contexts, it is difficult to ascertain whether these lessons are transferable.

To fill this evidence gap, we conducted a mixed-methods evaluation of rural, community-managed WSP implementations in four countries to quantify the outcomes of, and develop recommendations for, implementing rural, community-managed WSPs.

3.3 Materials and Methods

This study was completed using a mixed-methods protocol, including: site selection, assessment of WSP implementation, household surveys, water quality testing, sanitary surveys, key informant interviews and focus group discussions, and data analysis. Protocols were approved by the Tufts University Institutional Review Board and the local ethics review process in each country.

3.3.1 Country selection

Working in coordination with UNICEF, four countries - India, the Democratic Republic of the Congo (DRC), Fiji, and Vanuatu - were selected based upon WSP programming by UNICEF and their implementing partners. Assessment visits to each country were carried out 7-12 months prior to the operational research to ascertain the local WSP implementation program details, and develop an appropriate evaluation plan.

3.3.2 Site selection

The target was to randomly survey 100 households in WSP villages and 100 households in non-WSP villages per country, as this sample would show a statistically significant difference in *Escherichia coli* (*E. coli*) concentrations in water samples. In two states in India, WSP villages were defined as those that operated water supplies under the supervision of a village water technician and non-WSP villages were those that did not. In DRC, the study was conducted in one health zone, where WSP villages were defined as those that had received certification in the comprehensive 8-step WASH training program, Village Assaini, from the Ministry of Health, and controls were villages in early stages of the program that had not yet achieved certification. On three islands in Fiji and two islands in Vanuatu, WSP villages were those that received training from implementing partners under the Drinking Water Safety and Security Plan program, and controls were communities that had not yet entered the process.

Implementing partners and UNICEF Country Offices in India, Fiji, and Vanuatu provided lists of WSP villages, from which 10 were randomly selected for study inclusion. Ten non-WSP villages with similar locations and populations were used as control communities. Ten households per village were randomly selected for participation by starting in the village center and skipping a pre-determined number of houses. In DRC, implementing partners and UNICEF provided lists of certified villages, from which 20 were randomly chosen for inclusion. Twenty non-WSP villages with similar locations and populations were used as control communities. Households were selected in the same random manner, but the number of households visited per village was determined by sampling 3.5% of households in the village per Department of Health request.

3.3.3 WSP Implementation Assessment

WSP implementations were evaluated in each country based on the WSP for Small Community Water Supplies list of tasks: 1) engage community and assemble WSP team; 2) describe community water supply; 3) identify hazards, hazardous events, and existing control measures; 4) develop and implement an incremental improvement plan; 5) monitor control measures and verify effectiveness of WSP; and, 6) document, review, and improve all aspects of WSP implementation.14 For each task, a country was rated (-) for no inclusion during implementation, (✓–) for partial implementation of the task, (✓) for basic inclusion of all elements of the task, and (✓+) for detailed and thorough inclusion of all elements of a task. A numerical score was assigned to each rating (0-3) and a country sum was calculated out of 18 possible points.

3.3.4 Household surveys

Household surveys were carried out in the local language on paper surveys by trained enumerators (Annex A). Surveys were developed generally for the project, adapted for local context, and pre-tested during enumerator training in each country. Surveys comprised 57-60 questions and observations on household demographics; knowledge, attitudes, and practices towards WASH; and, knowledge of village water committees and WSP work.

3.3.5 Water quality tests

During each household survey, a household collection-point water sample (e.g. a local tapstand, hereafter termed "source") and household stored water sample (if available) was collected aseptically in 125 mL WhirlPak™ bags with sodium thiosulfate (Nasco, Fort Atkinson, WI, USA). Samples were placed on ice and transported to a field laboratory for subsequent microbiological and turbidity analysis within 12 hours of collection. If ice was unavailable, samples were processed immediately after collection. Water samples were prepared using standard methods of membrane filtration for simultaneous detection of total coliforms and *E. coli* with m-ColiBlue24 media (Hach Company, Loveland, CO, USA). Samples were diluted with sterile buffered water, vacuum filtered aseptically through a 45-micron filter (EMD Millipore, Billerica, MA, USA), placed in a plastic petri dish with a media-soaked pad, and incubated for 24 hours at 35ºC. Colonies were counted and concentrations calculated by averaging plate counts within a countable range (10-200 colony forming units (CFU)/plate) after accounting for dilution factors. Ten percent of samples were duplicated, and a sterile buffered water blank was run every 20 plates. Turbidity was measured with a calibrated LaMotte 2020 turbidimeter (Chestertown, MD, USA). At the household, enumerators measured temperature, pH, and EC of water samples with an Oakton PCSTestr 35 WD-35425-10 multi parameter probe (Oakton, Vernon Hills, IL, USA). If water was reported to be treated with chlorine, free chlorine residual and total chlorine residual were measured with a Hach CN-66 color wheel test kit with DPD-1 and DPD-3 reagents.

3.3.6 Sanitary surveys

Enumerators conducted a sanitary survey at household sources in Fiji and Vanuatu only, as they are part of WSP implementations in Fiji and Vanuatu. Sanitary survey assessment questions were dependent on source type, and based on WHO's surveys and risk scoring guide (World Health Organization 1997). Every identified risk was given one point and the sum of identified risks was the reported source risk score. Maximum possible scores were 5 for a tap stand, 10 for rainwater catchment, and 11 for an open, hand-dug well. The risk score was sorted into the WHO categories of low, intermediate, high, and very high.

3.3.7 Key informant interviews and focus group discussions

Key informant interviews (KII) and focus group discussions (FGD) contained 5-34 primarily qualitative questions and were carried out in the local language by trained enumerators (Annex B). KIIs were conducted with village chiefs, plumbers, and water maintainers/quality testers. FGDs were held with water management committees, village healthcare workers, and village WASH committees as appropriate to the local context. Qualitative data from the FGDs and KIIs were analyzed and summarized according to five themes pertinent to the implementation of WSPs that evolved during discussions: documentation, risk identification and assessment, water safety, water security, and capital and technical assistance. Villages considered successful at documentation would have: a water management committee with formally recorded and gender balanced membership, a schedule for regular meetings, meeting minutes, action plans, delineated responsibilities, and schematics of water supply systems. Villages considered able to successfully identify and assess risks could: identify and prioritize hazards, characterize types of risk, and identify control measures. Villages that manage water safety would have: an understanding of water quality assessment, the ability to test water quality, operational measures to maintain quality to the point-of-consumption, and procedures alerting users about a water safety emergency. Villages that manage water security would have: an understanding of water supply/demand amounts and patterns of usage, action on water access issues, and measures to address seasonality of the supply. Villages that manage capital and technical assistance would: fundraise for their system, organize maintenance and upgrades, and solicit external assistance where required.

3.3.8 Analysis

Data was manually recorded, entered into Microsoft Excel 2010 (Redmond, Washington, USA), and cleaned and statistically analyzed using R 3.3.2 (Vienna, Austria). Microbiological water quality results were grouped by the WHO's disease risk classification levels of: conforms to guidelines (<1 *E. coli* CFU/100mL), low risk (1-10 CFU/100mL), medium risk (>10-100 CFU/100mL), and high risk (>100 CFU/100mL) (World Health Organization 1997). Additionally, by country, a Fisher's exact statistic test of independence was conducted for each type of water sample to compare WSP to control households at two grouped classification levels: samples conforming (<1 CFU/100mL) vs. non-conforming and samples <10 CFU/100mL vs. ≥10 CFU/100mL. For non-normal data, paired Wilcoxon signed rank tests were performed on log-transformed values to compare geometric mean *E. coli* concentrations of household source water to stored water when both samples were collected, and independent Mann-Whitney-U tests were performed to compare the geometric mean *E. coli* concentrations for WSP and control household source and stored water respectively. For all statistical tests, p-values <0.05 were considered significant. Where gathered, sanitary survey risk scores were grouped and plotted against the water source's corresponding log *E. coli* CFU/100mL concentration.

3.4 Results

This study was carried out between August-December, 2016. In total, 816 household surveys, 1,113 water samples, 120 key informant interviews, and 136 focus groups were conducted across the four-country study.

3.4.1 WSP Implementation

The level of WSP implementation was assessed through a combination of: 1) information on WSP programming gathered during assessment trips; and 2) from KIIs and FGDs during the evaluations. WSP implementations varied from minimal programming in India to thorough front-end WSP processes in Fiji and Vanuatu. All implementations lacked back-end WSP principles of regular monitoring, verification, and review (Table 3-1).

In India, WSP implementation scored a 6/18 where there were water committees but not dedicated WSP teams, some hazard identification, limited knowledge or follow through of improvement plans, yearly water quality monitoring, but no verification, documentation, or improvement of the WSP. In DRC, WSP implementation scored a 7/18 where there was integration of community water committees, descriptions of water supply systems, improvement plans implemented where possible, but no control monitoring, verification, documentation, or review of WSP implementation. In Fiji and Vanuatu, WSP implementations were orchestrated under the same general programming plan and scored 13/18 where there were trained WSP teams, thorough descriptions of water systems including supply and demand amounts, identification of hazards and control measures, but little verification of effectiveness or review of the WSP.

Table 3-1: Level of WSP implementation based upon 2012 WHO Small Supply Guidelines

	India	DRC	Fiji	Vanuatu
Task 1 - Engage community and assemble WSP team	✓–	✓	✓+	✓+
Task 2 - Describe community water supply	✓	✓	✓+	✓+
Task 3 - Identify hazards, hazardous events, existing control measures	✓–	✓–	✓+	✓ +
Task 4 - Develop and implement an incremental improvement plan	✓–	✓	✓	✓
Task 5 - Monitor control measures and verify effectiveness of WSP	✓–	–	✓–	✓–
Task 6 - Document, review, and improve WSP implementation	–	–	✓–	✓–

Score assignment: — = 0 ✓– = 1 ✓ = 2 ✓+ = 3

3.4.2 Household Surveys

In total, 200 households (HH) were surveyed in India (100 in WSP and 100 in non-WSP villages); 206 in DRC (100 in WSP villages and 106 in non-WSP villages); 200 in Fiji (100 in WSP villages and 100 in non-WSP villages); and, 210 in Vanuatu (110 in WSP villages and 100 in non-WSP villages). In all four countries, the majority of survey respondents were the female head of household (Table 3-2). Respondents in India and Fiji had predominantly attained some secondary education; in Vanuatu >50% of WSP respondents had a primary education, while <50% of all respondents in DRC had any schooling. Mean HH size was similar between WSP and control communities in all countries.

Over 90% of respondents in India, DRC, and Fiji reported believing that you can get sick from water; in Vanuatu more WSP respondents (70%) than control (47%) reported the same (p=0.032).

Across all four countries the most common reported water-related illness was diarrhea; fever and vomiting were also noted in all countries, while cholera was only reported in India and DRC. In all four countries, the top reported reason for believing water was safe to drink was “if the water is clear”; and for believing water was not safe to drink was “if the water is dirty.”

The primary source of HH drinking water varied by country and within countries (Table 3-3). Indian HHs used tube wells (75% WSP, 78% control) and HHs in Vanuatu used rainwater (53% WSP, 78% control). In DRC, 48% of WSP HHs reported utilizing a public tap from a piped water supply; 53% of control reported using a protected spring. In Fiji, WSP HHs utilized private piped taps (31%), protected springs (22%) and rainwater (22%), while control communities predominantly used private piped taps (79%). The distribution of primary source was different between WSP and control HHs in DRC and Fiji ($p<0.001$ for each).

In India, Fiji, and Vanuatu the median roundtrip time to collect water was ≤10 minutes, in DRC it was 60 minutes. The mean number of times a HH collected water per day ranged from 2.1 in DRC to 8.4 in WSP HHs in Fiji. Over 50% of respondents in each country reported drinking water from secondary sources; this was highest in the Pacific with >80% of WSP and control HHs using secondary sources, and in WSP HHs in DRC (83%). The percentage reporting payment of a monthly water fee was highest in WSP HHs in India, DRC, and Vanuatu (57%, 64%, 73%, respectively), while no respondent reported paying in Fiji. More HHs paid for water in WSP villages in DRC and Vanuatu ($p<0.001$ each); the mean cost was lower in WSP villages in DRC ($p<0.001$).

Table 3-2: Household demographics and drinking water beliefs by country

	India		DRC		Fiji		Vanuatu	
	WSP	Control	WSP	Control	WSP	Control	WSP	Control
% Female respondents	63	53	82	78	66	57	60	58
Mean (range) respondent age	42.3 (18-79)	40.6 (17-75)	36.3 (18-72)	39.0 (18-85)	47.8 (22-78)	47.8 (16-85)	49.4 (13-86)	44.5 (17-84)
% Reported highest education level reached								
No education	8	6	50	61	2	2	3	2
Some or completed primary	9	12	29	21	40	36	56	44
Some secondary or higher	79	82	21	16	60	63	43	52
Mean (range) number of people per household	5.0 (2-14)	6.1 (2-17)	6.9 (2-12)	6.0 (2-12)	5.0 (1-10)	4.7 (1-11)	5.1 (1-16)	5.5 (1-14)
% Respondents believe you can get sick from water	96	95	91	100	100	96	70	47
% Top reported sicknesses that you can get from water	Diarrhea (79) Stomach ache (58) Vomiting (48)	Diarrhea (80) Stomach ache (47) Vomiting (44)	Diarrhea (80) Fever (38) Cholera (35)	Diarrhea (74) Cholera (56) Fever (44)	Diarrhea (97) Stomach ache (93) Vomiting (84)	Diarrhea (100) Stomach ache (99) Vomiting (86)	Diarrhea (78) Stomach ache (23) Fever (23)	Diarrhea (89) Fever (57) Stomach ache (10)
% Top reported reasons that respondents believe water is safe to drink	Water clear (90) Boiled (33) Source clean (27)	Water clear (93) Boiled (28) Source clean (21)	Water clear (55) Source clean (37) Storage clean (15)	Water clear (56) Source clean (42) Storage clean (17)	Water clear (59) Boiled (36) Storage clean (34)	Water clear (88) Storage clean (42) Filtered (26)	Water clear (55) Bottled (24) Boiled (17)	Water clear (76) Bottled (17) Filtered (7)
% Top reported reasons that respondents believe water is *not* safe to drink	Water dirty (95) Makes you sick (32) Bad source (27)	Water dirty (100) Makes you sick (21) Has bacteria (19)	Water dirty (48) Bad source (19) Storage dirty (14)	Water dirty (48) Bad source (31) Makes you sick (25)	Water dirty (72) Makes you sick (66) Storage dirty (47)	Water dirty (90) Makes you sick (58) Storage dirty (41)	Water dirty (78) Storage dirty (16) Makes you sick (13)	Water dirty (85) Storage dirty (15) Has bacteria (14)
% Respondents believe their current drinking water is safe	96	96	81	76	88	82	62	66

Table 3-3: Household drinking water source, collection, and storage practices by country

	India		DRC		Fiji		Vanuatu	
	WSP	Control	WSP	Control	WSP	Control	WSP	Control
% Top three most reported primary drinking water sources	Tube well (75) Pub. piped tap (18) Purchased (3)	Tube well (78) Priv. piped tap (13) Purchased (4)	Pub. piped tap (48) Protec. spring (34) Unprotec. spring (11)	Protec. spring (53) Pub. piped tap (17) Unprotec. spring (15)	Priv. piped tap (31) Protec. spring (22) Rainwater (22)	Priv. piped tap (79) Protec. spring (9) Surf. water (7)	Rainwater (53) Priv. piped tap (28) Open well (9)	Rainwater (78) Priv. piped tap (11) Open well (5)
Median (range) minutes of water collection trip	5 (0.5-60)	10 (0.5-120)	60 (10-480)	60 (10-360)	0.5 (0.5-10)	0.5 (0.5-3)	1.0 (0.017-150)	1.0 (0.033-60)
Mean (range) number of daily water collection trips	7.2 (0.3-20)	6.3 (1-20)	2.1 (1-8)	2.1 (0.3-20)	8.4 (1-30)	7.2 (1-27)	4.2 (0-20)	2.9 (1-10)
% Households report drinking from other sources	47	59	83	67	80	83	83	83
% Households pay water fee	57	57	64	20	0	0	73	43
Median (range) paid for water per month in USD	$0.78 (0.03-4.05)	$0.39 (0.04-9.33)	$0.14 (0.07-1.80)	$0.36 (0.07-15.08)	--	--	$0.90 (0.09-7.17)	$0.90 (0.45-10.76)
% Household had stored water	97	98	95	100	40	33	78	61
Top type storage container (%)	Metallic pot (53)	Metallic pot (54)	Jerrican (98)	Jerrican (100)	Plastic Bottle (73)	Plastic Bottle (43)	Bucket (60)	Bucket (48)
Median (range) liters of storage container	10 (0.5-20)	10 (0.1-100)	20 (5-60)	20 (3-60)	2 (1-26)	5 (1-10)	10 (1-1100)	5 (0.6-1200)
% Observed container covered	99	100	53	74	95	97	85	87
% Observed container had tap	20	13	24	47	52	85	48	79
% Observed water in container	98	98	93	98	84	94	83	90
% Treated water day of visit	5	2	0	0	4	21	15	5
Top treatment method (%)	Boiling (100)	Boiling (100)	--	--	Boiling (53)	Filter (55)	Boiling (88)	Boiling (80)
Median (range) hours since water collected	5 (0.08-24)	6 (0.08-48)	13 (0.17-96)	9 (1-96)	4.0 (0.5-96)	5.0 (1-12)	24.0 (0.5-250)	9 (1-1440)
Top obs. retrieval method (%)	Pouring (52)	Pouring (51)	Pouring (95)	Pouring (99)	Tap (68)	Tap (86)	Pouring (43)	Pouring (60)

During the survey, >95% of HHs in India and DRC; 78% of WSP and 61% of control HHs in Vanuatu; and, 40% of WSP and 33% of control HHs in Fiji reported storage of water (Table 3). The primary storage container varied by country, with metallic pots most popular in India (53% WSP, 54% control), jerricans in DRC (98% WSP, 100% control), plastic bottles in Fiji (73% WSP, 43% control), and buckets in Vanuatu (60% WSP, 48% control). Over 99% of HHs reporting storage in India and >95% in Fiji had covered storage containers; more control HH containers were covered in DRC (53% WSP, 74% control containers, p=0.003). The most common retrieval method for water from a storage container was by pouring in India, DRC, and Vanuatu and by using a tap in Fiji. Reported water treatment was <5% in India and 0% in DRC; while it was reported in 4% of WSP and 21% of control HHs in Fiji (p=0.002) and 15% of WSP and 5% of control HHs in Vanuatu (p=0.022). The most common treatment method in Fiji was boiling in WSP HHs (53%) and filtration in control HHs (55%). Boiling was the top reported method in both WSP and control HHs in Vanuatu (88% and 80%, respectively).

3.4.3 Water Quality Testing

Risk categorization of water quality – WSP village water sources had more *E. coli* contamination than control village sources in DRC and Fiji at the <1 *E. coli* CFU/100mL classification level (p=0.009 and 0.020, respectively) and in Fiji and Vanuatu at the <10 CFU/100mL classification level (p<0.001 and p=0.004, respectively) (Table 3-4). WSP village households had more *E. coli* contamination than control village households in Fiji and Vanuatu at both the <1 CFU/100mL classification level (p=0.014 and 0.009, respectively) and the <10 CFU/100mL classification level (p=0.001 and 0.002, respectively) (Table 3-5).

Water quality of household source and stored sample pairs – In India and Vanuatu there was no statistically significant difference in geometric mean *E. coli* CFU/100mL between source and stored sample pairs or between WSP and control villages (Table 3-6). In DRC, stored water had a higher geometric mean *E. coli* than source water in both WSP and control villages, indicating a safe storage issue (p<0.001 for both). Additionally, WSP village sources had higher geometric mean *E. coli* than control village sources (p<0.001). In WSP villages in Fiji, source and stored water did not have different geometric mean *E. coli* (p=0.427), while in control villages stored water had less geometric mean *E. coli* than source water (p=0.033). Furthermore, WSP villages had higher geometric mean *E. coli* in both source and stored water samples than control villages (p<0.001 for both). Results for geometric mean total coliforms were similar to *E. coli*; geometric mean turbidity varied between source and stored samples in India (WSP: p=0.029; Control: p=0.003) (Table 3-7 and Table 3-8)

Table 3-4: N(%) household source water samples by WHO disease risk category (*E. coli* CFU/100mL)

	n	Conforms (<1)	Low Risk (1-10)	Medium Risk (>10-100)	High & Very High Risk (>100)	Fisher p-value (<1)	Fisher p-value (<10)
India WSP	27	2 (7%)	3 (11%)	14 (52%)	8 (30%)	0.593	0.720
India Control	31	1 (3%)	3 (10%)	22 (71%)	5 (16%)		
DRC WSP	30	5 (17%)	13 (43%)	8 (27%)	4 (13%)	0.009*	1
DRC Control	18	10 (56%)	1 (6%)	1 (6%)	6 (33%)		
Fiji WSP	99	10 (10%)	15 (15%)	57 (57%)	17 (17%)	0.020*	<0.001*
Fiji Control	97	22 (24%)	38 (42%)	25 (28%)	12 (12%)		
Vanuatu WSP	84	40 (48%)	13 (16%)	22 (26.2%)	9 (11%)	0.373	0.004*
Vanuatu Control	97	46 (54%)	26 (29%)	3 (5%)	11 (11%)		

* Significant at alpha = 0.05 level

Table 3-5: N(%) household stored water samples by WHO disease risk category (*E. coli* CFU/100mL)

	n	Conforms (<1)	Low Risk (1-10)	Medium Risk (>10-100)	High & Very High Risk (>100)	Fisher p-value (<1)	Fisher p-value (<10)
India WSP	101	3 (3%)	0 (0%)	81 (80%)	17 (17%)	1	0.082
India Control	100	3 (3%)	6 (6%)	70 (70%)	21 (21%)		
DRC WSP	96	0 (0%)	31 (39%)	39 (41%)	26 (27%)	1	0.379
DRC Control	106	0 (0%)	41 (39%)	24 (23%)	41 (39%)		
Fiji WSP	38	5 (13%)	5 (13%)	21 (55%)	7 (18%)	0.014*	0.001*
Fiji Control	48	18 (38%)	12 (25%)	15 (31%)	3 (6%)		
Vanuatu WSP	82	29 (35%)	12 (15%)	26 (32%)	15 (18%)	0.009*	0.002*
Vanuatu Control	55	32 (58%)	10 (18%)	7 (13%)	6 (11%)		

* Significant at alpha = 0.05 level

Table 3-6: Geometric mean (range) *E. coli* CFU/100mL household source and stored water sample pairs

		n	Source Water	Stored Water	p-value[a]
India	WSP	48	12.2 (<1-9,700)	6.5 (<1-2,001)	0.245
	Control	32	28.1 (<1-2,001)	7.2 (<1-2,001)	0.634
	p-value[b]		0.053	0.816	
DRC	WSP	94	12.5 (<1-2,000)	42.1 (<10-2,500)	<0.001*
	Control	95	5.1 (<1-4,000)	75.5 (<10-17,300)	<0.001*
	p-value[b]		<0.001*	0.134	
Fiji	WSP	37	34.8 (<1-1,280)	22.7 (<1-1,340)	0.427
	Control	46	7.6 (<1-740)	3.7 (<1-190)	0.033*
	p-value[b]		<0.001*	<0.001*	
Vanuatu	WSP	56	4.1 (<1-357)	5.4 (<1-680)	0.145
	Control	52	2.6 (<1-2,001)	2.3 (<1-377)	0.820
	p-value[b]		0.203	0.061	

a – Wilcoxon Signed Rank p-value for nonparametric paired samples
b – Mann-Whitney-U p-value for nonparametric paired samples
* Significant at alpha = 0.05 level

Table 3-7: Geometric mean (range) Total Coliforms CFU/100 mL household source and stored sample pairs

		n	Source Water	Stored Water	p-value[a]
India	WSP	48	1032.5 (<10-14,100)	722.5 (6-3,880)	0.090
	Control	32	1129.9 (<10-18,400)	639.1 (11-2,240)	0.124
	p-value[b]		0.604	0.996	
DRC	WSP	94	239.7 (6-4,400)	1199.4 (<10-13,400)	<0.001*
	Control	95	72.7 (<1-11,400)	2219.0 (9-18,200)	<0.001*
	p-value[b]		0.008*	0.002*	
Fiji	WSP	37	995.4 (13-3,620)	1051.7 (<1-3,920)	0.431
	Control	46	1434.3 (64-3,860)	603.0 (<1-3,520)	0.006*
	p-value[b]		0.424	0.225	
Vanuatu	WSP	56	48.0 (<1-2,670)	201.5 (<1-3,640)	<0.001*
	Control	52	48.2 (<1-2,860)	229.0 (<1-3,120)	0.001*
	p-value[b]		0.978	0.958	

a – Wilcoxon Signed Rank p-value for nonparametric paired samples
b – Mann-Whitney-U p-value for nonparametric paired samples
* Significant at alpha = 0.05 level

Table 3-8: Geometric mean (range) turbidity (NTU) household source and stored sample pairs

		n	Source Water	Stored Water	p-value[a]
India	WSP	48	8.74 (1.17-24.40)	6.67 (2.14-13.70)	0.029*
	Control	32	9.86 (1.21-51.10)	5.64 (0.72-26.50)	0.003*
	p-value[b]		0.311	0.772	
DRC	WSP	94	2.04 (0.51-96.70)	2.69 (0.76-26.60)	<0.001*
	Control	95	3.10 (0.92-58.70)	3.11 (0.93-21.30)	0.9128
	p-value[b]		<0.001*	0.105	
Fiji	WSP	37	2.70 (1.20-11.70)	3.03 (1.29-15.40)	0.262
	Control	46	3.32 (0.71-13.90)	2.25 (0.81-8.57)	<0.001*
	p-value[b]		0.066	0.092	
Vanuatu	WSP	56	1.87 (0.96-8.18)	1.95 (0.89-6.32)	0.320
	Control	52	2.29 (0.71-35.10)	2.30 (0.76-27.80)	0.761
	p-value[b]		0.125	0.669	

a – Wilcoxon Signed Rank p-value for nonparametric paired samples
b – Mann-Whitney-U p-value for nonparametric paired samples
* Significant at alpha = 0.05 level

3.4.4 Sanitary Surveys and Water Quality

The mean risk score for rainwater harvesting was 2.4/10 (range: 0/10-6/10) in Fiji and 4.4/10 (range: 0/10-10/10) in Vanuatu. For a piped water supply tap the mean risk score was 1.5/5 (range: 0/5-5/5) in Fiji and 3.3/5 (range: 0/5-5/5) in Vanuatu. In Vanuatu, there were also open dug wells with a mean risk score of 6.9/10 (range: 2/10-10/10). There was no clear trend between the risk score and log-transformed *E. coli* concentration or between groupings in the risk matrices (Table 3-9 and Table 3-10).

Table 3-9: Fijian source water risk matrix for DWSSP and Control villages; reported values are the number of sites within each *E. coli* level that correspond with a sanitary risk score

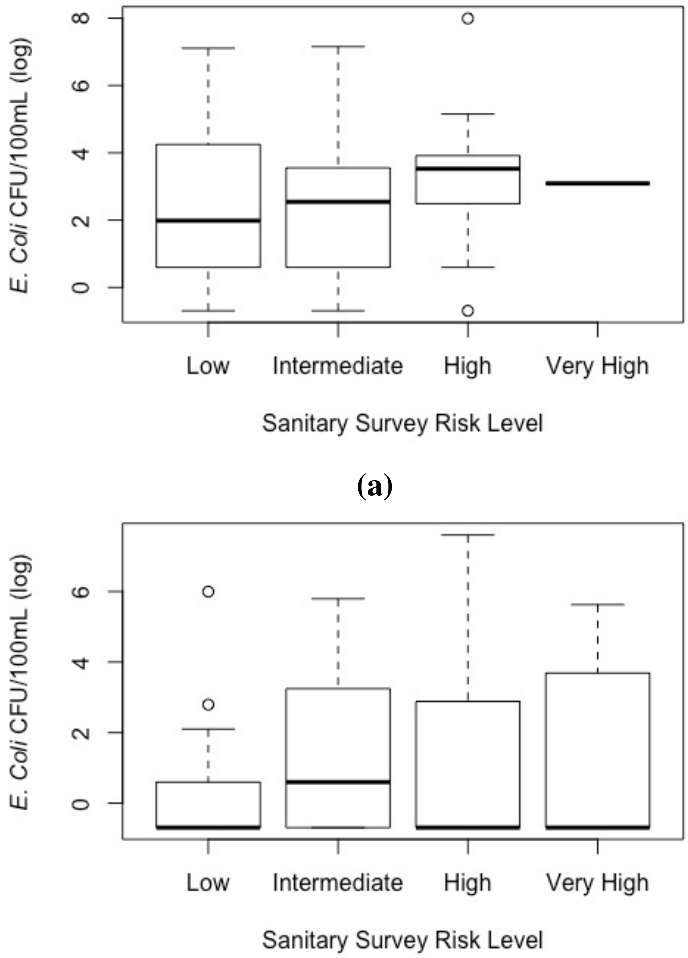
	Sanitary Inspection Risk Score				
***E. coli* (CFU / 100 mL)**	"No" Risk*	Low Risk	Intermediate Risk	High Risk	Very High Risk
>100	2[a] 0[b]	6[a] 7[b]	3[a] 0[b]	1[a] 0[b]	0[a,b]
10-100	2[a] 2[b]	27[a] 19[b]	11[a] 1[b]	0[a,b]	0[a,b]
1-10	0[a] 5[b]	7[a] 24[b]	3[a] 3[b]	0[a,b]	0[a,b]
<1	0[a] 4[b]	6[a] 13[b]	2[a] 1[b]	0[a,b]	0[a,b]
	No action required	Low action priority	High action priority	Urgent action required	

* – "No" risk indicates a score of 0 on the sanitary survey
a – DWSSP villages
b – Control villages

Table 3-10: Vanuatu source water risk matrix for DWSSP and Control villages; reported values are the number of sites within each *E. coli* level that correspond with a sanitary risk score

	Sanitary Inspection Risk Score				
***E. coli* (CFU / 100 mL)**	"No" Risk	Low Risk	Intermediate Risk	High Risk	Very High Risk
>100	0[a,b]	1[a] 0[b]	5[a] 4[b]	1[a] 2[b]	0[a,b]
10-100	0[a,b]	11[a] 1[b]	4[a] 5[b]	2[a] 4[b]	0[a,b]
1-10	0[a,b]	8[a] 4[b]	0[a] 11[b]	1[a] 4[b]	0[a,b]
<1	0[a] 3[b]	16[a] 6[b]	10[a] 17[b]	2[a] 19[b]	7[a] 1[b]
	No action required	Low action priority	High action priority	Urgent action required	

* – "No" risk indicates a score of 0 on the sanitary survey
a – DWSSP villages
b – Control villages



(a)

(b)

Figure 3-1: Box plot of sanitary survey risk level and log *E. coli* of water sources for (a) FIji; (b) Vanuatu

3.4.5 Focus Group Discussions and Key Informant Interviews

Key points associated with the five identified themes from the KIIs and FGDs are summarized, including documentation, risk identification and assessment, water safety, water security, and capital and technical assistance.

Documentation – Documentation of meeting minutes and outcomes was common for water committees in all countries regardless of training on WSPs. Evidence of meetings was often sent to local authorities in India, DRC, and Fiji in compliance with local policy, motivating the continued use of the process. Maps of source points and water supply distribution systems were uncommon (excepting WSP villages in Fiji); villages relied upon informal knowledge of source and tap locations. In DRC, Fiji, and Vanuatu most WSP trained communities had documented improvement plans, while control villages had 'wish-lists.' In India, villages kept plans for the installation of small sources, but the district kept improvement plans for large infrastructure.

Risk Identification and Assessment – Control villages in Fiji and Vanuatu, as well as all water management committees in DRC, indicated pipe breakages as the primary monitored and mitigated hazard. Additional risk identification was based on sanitary surveys in WSP trained villages in Fiji and Vanuatu and Department of Health colored risk score cards in Indian villages. There was no procedural risk prioritization indicated by discussions in any country, regardless of WSP training. A reactive approach to managing risks was discussed in all countries, frequently associated with obstruction of water delivery.

Water Safety – No regular water quality testing was documented in DRC, Fiji, or Vanuatu regardless of WSP implementation. In India, water quality was tested on a rotating schedule by the district per national guidelines. Treatment of water sources was discussed in India (i.e., bleaching powder at open wells and piped water systems in some villages) and in Fiji (i.e., community slow sand filters in two control villages). HH water treatment was advocated by community health workers during rainy seasons and outbreaks (India and DRC) and during emergencies (Fiji and Vanuatu).

Water Security – Water availability issues were discussed in all four countries. In India, the government had a well water-level monitoring project to watch for indications of drought. In DRC water security concerns included, unknown water usage amounts, uneven coverage of piped water systems and point sources, and long distances from HHs to their water source. In Fiji, six WSP villages and zero control villages were able to calculate their water supply and demand. All communities in Vanuatu, indicated water shortages, particularly during El Niño seasons.

Capital and Technical Assistance – Water fees were collected in Vanuatu communities regardless of WSP implementation and by one water committee in DRC. Stakeholders in DRC, Fiji, and Vanuatu all indicated the need for external financial assistance with water system upgrades. In India, villages fundraised for installation and maintenance of community tube wells while the district funded piped water supplies. Four WSP trained villages in Vanuatu had used their action plans to solicit external funding assistance. Tools distributed to communities varied by country, and were often cited as a source of confusion in India, where tools were minimal, and in DRC, where specific WSP tools were not given to the villages and implementer's tools were text-laden. However, in Fiji and Vanuatu the tools were pictorial and contained tick-boxes and decision trees with suggested solutions; these were discussed as being instructional technical assistance to maintainers. Stakeholders across all countries frequently requested more trainings on operation and maintenance, improvement plans, and risk assessment.

3.5 Discussion

Overall, we found: 1) incomplete WSP implementations; 2) no documented microbiological water quality improvements from WSPs; and, 3) small water supply operations improvements.

While implementers considered these WSPs, several implementations did not follow guidelines. In India, despite program labeling, there was no concerted WSP implementation for community-managed systems, only a water quality surveillance program. While conceptual integration of aspects of WSPs into the Village Assaini program was evident in DRC, actual use of WSP elements, particularly around risk assessment, was found to be deficient. In Fiji and Vanuatu, implementation trainings were clearly a WSP process, but continued use of WSPs by water committees was uncertain. This branding of non-WSP programs as WSPs perhaps comes from a perceived pressure at the country level to implement WSPs.

Despite promoting the delivery of safe drinking water, this study did not find any clear evidence linking WSP implementation with water quality improvements. This was not surprising as most communities lacked the means to regularly monitor the quality of their drinking water. Furthermore, there was no evidence of source water treatment in WSP communities in DRC, Fiji, and Vanuatu. Sanitary surveys showed no correlation with microbiological water quality in Fiji and Vanuatu, which is consistent with other studies indicating mixed results when comparing sanitary surveys to water quality (Bacci & Chapman 2011; Howard *et al.* 2003; Misati *et al.* 2017; Mushi *et al.* 2012; Parker *et al.* 2010). Water quality cannot be expected to improve in contaminated water sources without some form of treatment.

Secondary outcomes related to changes in the operation and maintenance of the water supply was found throughout this study. In India, DRC, and Vanuatu a larger portion of WSP households reported paying for water than in control communities. In WSP trained villages in Fiji and Vanuatu water system upgrades were based on technical calculations of their water supply and demand instead of ad-hoc improvements. Changes in the operation of a water supply as a result of a WSP is consistent with prior research.4, 10

The primary limitation of this study is that it did not capture baseline information about water system operation prior to WSP implementation, nor did it track changes in water quality longitudinally to determine the outcomes of WSP training. Although WSP and control communities were intended to be similar, during data analysis we found that water source types were not matched in DRC and Fiji, nor was the frequency and type of water treatment in Fiji, which reflects the realities of varied water supply situations. Due to conflicting schedules it was difficult to have all relevant stakeholders present at KIIs and FGDs; we estimate that 70% of FGDs and KIIs had all stakeholders involved. Despite these limitations, we feel the data and lessons learned from the case studies add value.

If WSPs are to be employed, the following are recommendations for their implementation in rural, community-managed systems in developing countries.

1) Provide sufficient training and simplify tools through the use of 'tick-boxes' and decision diagrams.

2) Motivate community-level WSP uptake via supervision and encouragement from an external body, preferably governmental to achieve long-term sustainability.

3) Integrate full WSP programming into existing WASH programs where possible to reduce duplication of effort.

4) Promote water treatment and monitoring of water quality at either the community or household level.

5) Establish financing and technical assistance to provide villages with more permanent solutions to WASH infrastructure deficiencies identified during WSP implementation.

3.6 Conclusions

Our research on the effectiveness of extending WSPs from large, urban systems to community-managed supplies identified three core challenges: 1) villages with multiple (private) drinking water sources may not have full WSP coverage, thereby limiting the potential for WSP benefits and questioning the appropriateness of WSP implementations in these settings; 2) to ensure WSP processes are not diluted, thorough training of trainers and training of villages on the complete six-task WSP implementation is critical; and, 3) resource support is required for design, hardware, and technical services to improve drinking water quality. The mixed evidence found herein on WSP implementations in community-managed, rural water supplies highlights both the need for further development of usable WSP processes (including accounting for mixed/multiple water sources, training, and resourcing) tailored to community-managed supplies; and, the risks in recommending WSPs for community-managed supplies in the absence of these processes.

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3.8 Citation

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4 Investigation of the Pore Network Morphology of Ceramic Water Filters

4.1 Introduction

4.1.1 Ceramic water filters: background

There are several types of ceramic water filters for use as a household water treatment (HWT) option, including candle and pot models. For the pot model, a colloidal silver enhanced ceramic pot filter is placed on top of a collection receptacle with a spigot and covered with a lid (Figure 4-1). The filters are locally manufactured by various organizations of different production capacities throughout the world (The Ceramics Manufacturing Working 2011). The filters are produced by mixing a burn-out material, such as rice husk, sawdust, or other similarly organic material, with locally available clay at an experimentally determined ratio. The mixture is then pressed in a mold, dried, and fired in a kiln with a firing schedule that allows for the combustion of the burn-out material at lower temperatures prior to the occurrence of the ceramic change. Firing is stopped prior to vitrification to preserve the porous nature of the filters. Once cooled, the filters visually inspected and their flow rate tested for quality control. On average a filtering element is designed to filter 1-3 L of water per hour when fully saturated during the first hour of a flow rate test. Filters flowing slower than the recommendation will not be user-accepted and will not function as a filter, while those flowing faster may contain cracks and will not allow enough contact time between the water and the colloidal silver on the walls.

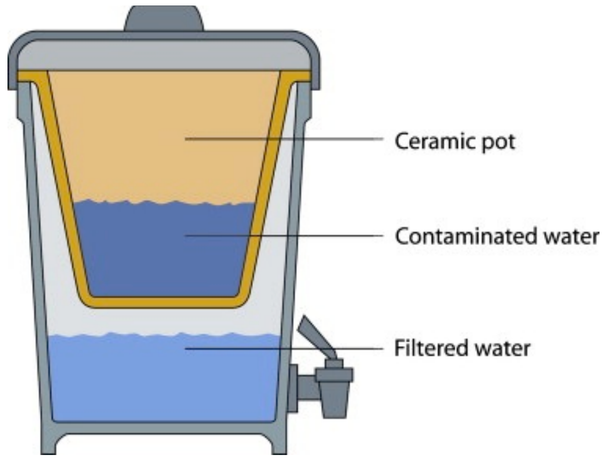


Figure 4-1: Ceramic pot water filter and storage container set-up (van Halem, 2007)

4.1.2 Ceramic water filter: effectiveness at improving water quality

Because ceramic pot filters rely on the physical removal of contaminants via pore size exclusion and adsorption, they are quite effective against the removal of bacteria and protozoa (World Health Organization 2016). Many studies, in both the field and laboratory, have been conducted on the microbiological effectiveness of ceramic pot filters. The filters have been shown to be effective at removing 90-99.99% of bacterial organisms (Brown & Sobsey 2006; Brown 2007; Johnson *et al.* 2008; Roberts 2004) and in field studies improving water to the WHO "low-risk" classification of <10 *E. coli* per 100 mL (Brown 2007; Johnson *et al.* 2008; Roberts 2004). Further, ceramic pot filters have demonstrated >99% removal of protozoan (Lantagne 2001; van Halem *et al.* 2007).

The range of pore sizes in the filters do not allow for effect mechanical removal of viruses, so the filters are coated in a bacteriostatic element, either colloidal silver or silver nitrate (Bielefeldt *et al.* 2010). Improvements to the microbiological effectiveness of the ceramic filters through the application of colloidal silver have been shown in several studies (Bielefeldt *et al.* 2010; Lantagne 2001; Oyanedel-Craver & Smith 2008; van Halem *et al.* 2007) and has been seen to additionally benefit the lifetime of the filter by preventing biological growth on the surface (van Halem *et al.* 2007) and preventing growth in the storage receptacle (Bloem *et al.* 2009). Although the promoted method of colloidal silver application is brushing, other methods such as dipping and firing into the filter have also demonstrated effectiveness; the more important variable in silver application is the quantity used (Lantagne *et al.* 2010; Oyanedel-Craver & Smith 2008). Results on the application of silver nitrate have been mixed, with one study showing improved microbiological efficacy (Bloem *et al.* 2009) and another showing none (Brown *et al.* 2007).

4.1.3 Ceramic water filters: morphology and modeling

Ceramic pot filter manufacturing is highly variable both between and within factories; coupled with the fact that they are manufactured with different burn-out materials and clays it is anticipated that the resulting ceramic membrane pore network will vary between filters (Rayner *et al.* 2013). A classic description of any pore network identifies three-primary pore types - dead-end pores, interconnected pores, and isolated pores - and is appropriate for application to the ceramic pot filter system (Figure 4-2). Dead-end pores impede flow through the medium and result in regions where retentate builds up. Interconnected pores are pores that allow flow to pass through and are connected by pore throats. Isolated pores are those that do not participate in the flow of the filtrate; in ceramic filters they are typically nano- or meso-pores that are a result of the ceramic matrix and not of the engineered pores resulting from burn-out material.

Several studies have classified ceramic pot filter pore morphology, using either samples from a field manufactured filter or a laboratory produced ceramic disk (Matthies *et al.* 2015; Oyanedel-Craver & Smith 2008; Plappally *et al.* 2009; Rayner *et al.* 2017; Scannell 2016; van Halem *et al.* 2007; Yakub *et al.* 2013). To calculate porosity comparisons of filter weight at full saturation and when dried have been used (Scannell 2016; van Halem *et al.* 2007). Pore size distributions have been determined via Mercury Intrusion Porosimetry (MIP), which takes advantage of Washburn's equation and the assumption that pores are cylindrical, to calculate the volume of pores intruded by mercury at increasing pressures and relating to the cylinder (pore) diameter ((Matthies *et al.* 2015; Oyanedel-Craver & Smith 2008; Plappally *et al.* 2009; van Halem *et al.* 2007; Washburn 1921; Yakub *et al.* 2013).

Figure 4-2: Primary pore classifications (van Halem *et al.* 2007)

Permeability of ceramic pot filter pore networks has been calculated using MIP data in combination with the Katz-Thompson equation (Matthies *et al.* 2015; Oyanedel-Craver & Smith 2008; van Halem *et al.* 2007; Yakub *et al.* 2013) and from flow models (Annan *et al.* 2014; Matthies *et al.* 2015; Oyanedel-Craver & Smith 2008; Schweitzer *et al.* 2013; van Halem *et al.* 2007; Yakub *et al.* 2013). And tortuosity has been calculated using MIP and permeability data in either the Carman-Kozeny equation (Scannell 2016; van Halem *et al.* 2007) or by helium pncnometry method (Yakub *et al.* 2013). Finally, studies have used this measured and calculated information in combination with Darcy's law to determine hydraulic conductivity and filter flow rates (Annan *et al.* 2014; Matthies *et al.* 2015; Oyanedel-Craver & Smith 2008; Schweitzer *et al.* 2013; van Halem *et al.* 2007; Yakub *et al.* 2013) or have directly measured the permeability constant (Oyanedel-Craver & Smith 2008).

4.1.4 Computed Tomography

X-ray computed tomography (CT) is a non-invasive imaging technique effective at differentiating the internal composition of samples by taking advantage of a material's X-ray attenuation coefficient (Kalender 2006). The X-ray attenuation coefficient of a material is dependent on density, atomic number, and the X-ray photon energy of the source (Jackson & Hawkes 1981). With a relatively large field of view (mms) and 1 μm resolution, micro-scale X-ray CT is most fitting for determining ceramic water filter properties such as porosity, tortuosity, pore-size distribution and connectivity. Large samples are possible to image with a mosaic scan, where several smaller fields of view are stitched together. For microscale resolution, a synchrotron X-ray source is used in projection imaging, where the X-ray source and detectors remain stationary and a sample rotates on a rotation stage during image acquisition (Figure 4-3).

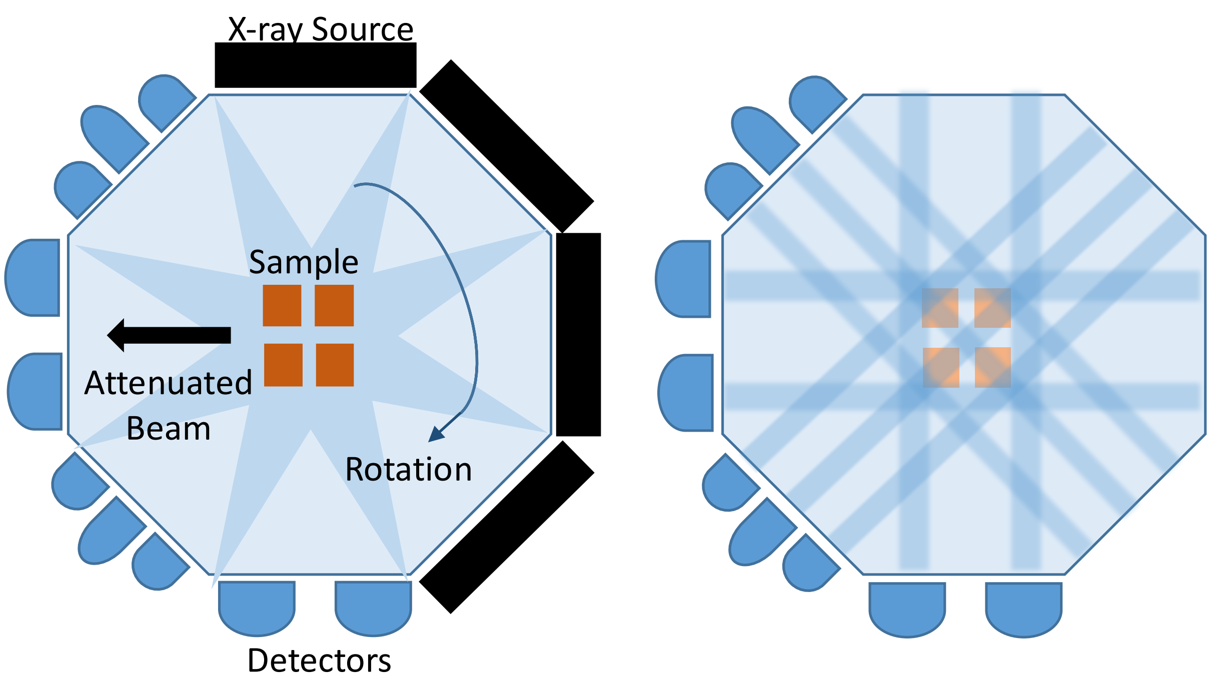


Figure 4-3: Set-up of X-ray CT scans, imaged at incremental projection angles

X-ray CT relies on capturing projections of the sample across a range of angles from 0°-180°. Each projection creates a line integral, which are collected over the range of rotation via the Radon transform, thereby producing a sonogram (Natterer & Wübbeling 2001) (Figure 4-4). The Filtered Back Projection algorithm is used to reconstruct the line sinograms in image space. Because the back projection is discrete, a summation of the Fast-Fourier Transform of each line sinogram is used to create 3D image volumes.

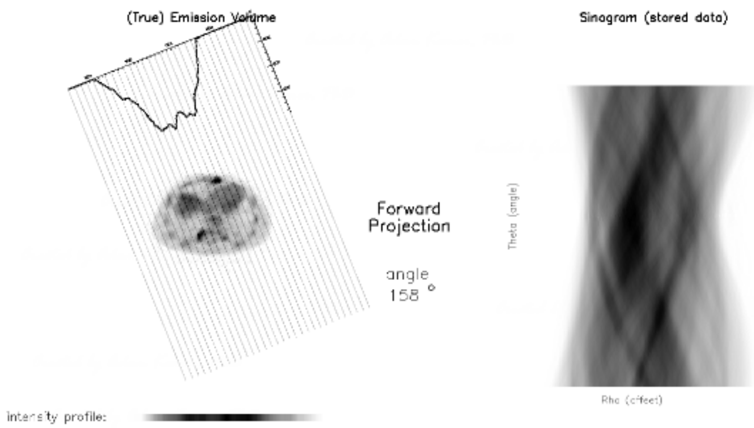


Figure 4-4: A sinogram (right) produced by capturing detected projection profiles of the sample (left) from 0°-180°, (UC Denver 2017)

4.1.5 Study Objectives

Because ceramic pot filters are locally produced, the measures used to certify the manufacture of a quality product are limited, with visual inspection for cracks and flow rate being the primary methods used (Rayner *et al.* 2013). The usefulness of flow rate as an indicator of microbiological effectiveness has been mixed, as one study found that *E. coli* removal did not very across a range of flow rates (Bloem *et al.* 2009), while another found that total coliform reduction fell below 99% in filters with a flow rate > 1.7 L/hr (Klarman 2009). The flow rate of the filters is predominantly affected by filter morphology, and morphology is primarily determined by the type and size of burn-out material (Hagan *et al.* 2009; Klarman 2009) type of clay (Oyanedel-Craver & Smith 2008), and the ratio of burn-out material to clay (Rivera-Garza *et al.* 2000). In a synopsis of best practices in ceramic filter production, the Ceramic Manufacturing Working Group (CMWG) highlighted research needs in each step of the filter manufacturing process. One key question CWMWG highlighted was "What role does particle size of the burn-out material play in pore structure and hydraulic properties? Is there an ideal particle size range for burn-out material?"(The Ceramics Manufacturing Working 2011).

Previous studies acknowledged in 4.2.3 have begun to answer that question, particularly in analyzing porosity, pore size distributions, and permeability. However, further research on important aspects of morphology, such as tortuosity and alignment of pores remains unknown. Further, a method for modeling the pore networks could prove useful as a way to rapidly study manufacturing parameters effect on functionality and provide direction for laboratory and field investigations. This study approaches ceramic filter pore network characterization by 1) developing a method to utilize X-ray micro-CT to image and subsequently process ceramic filter images; 2) validating the image processing method on four ceramic filter samples to characterize morphology; and, 3) proposing a method to extend the work to pore network models.

4.2 Methods

Samples from four different ceramic filters were preliminarily characterized and imaged using micro-CT. Images were 1) projected back with reconstruction; 2) downsampled and converted to 8-bit to reduce data size; 4) thresholded to separate solid and void; 5) stitched together so one mosaic represented each sample; and, 6) opened to reduce noise and ceramic matrix. The morphology of the samples, including porosity, pore size distribution, tortuosity, and formation factor were characterized. Lastly, a pore network extraction and pore network model of filtration were developed based upon laboratory flow testing of ceramic filters. All methods are described in detail in subsequent sections.

4.2.1 Samples

In total, samples from four different filters, representing four different factories were utilized in this research (Table 4-1). We obtained large samples from filters A and B that had been used in previous research, and full filters from the factories for filters C and D.

Table 4-1: Filter parameters

Sample	Country	Factory	Shape	Sample Location	Clay Source	Burn-out Material	Ratio Clay to Burn-out
A[1]	Dominican Republic	Atabey	Frustum	Wall	Various seams	Saw-dust (Pine or Acacia)	Unknown
B[2]	Dominican Republic	Filter Pure	Frustum	Wall	Single source seam	Saw-dust (Pine)	80:20
C	Kenya	Chujio	Frustum	Base	Unknown	Rice hull	Unknown
D	Tanzania	Safe Water Ceramics East Africa	Parabaloid	Base	Unknown	Saw-dust	Unknown

1 – Data from a factory report (Rayner 2013b)
2 – Data from a factory report (Rayner 2013a)

4.2.2 Sample preparation

Ten 4 mm x 4 mm rectangular cuboid samples, the length of which were the through thickness of the filter, were cut from each filter at random locations using a Dremel (Figure 4-5). From the prepared samples, four were chosen from each filter at the synchrotron facility for imaging and one was selected from each filter from the reconstructed images to be the representative sample for this project. Each of the four final samples were image processed for morphological characterization of the porous network, representing the filtering pathways of the ceramic water filter.

(a) **(b)**

Figure 4-5**:** (a) Cross section of wall of ceramic filter; (b) Cutting samples.

For the purposes of this research, the sample orientation was defined as a cuboid with planar views in ZX and YX (Figure 4-6).

4.2.3 Preliminary ceramic filter characterization

A cross section of a filter sample was imaged in a benchtop Phenom ProX scanning electron microscope (SEM) in the charge reduction vacuum mode. Images were collected by a backscatter electron (BSE) detector which detects elastically scattered electrons from a focused electron beam that is rastered across the surface (Figure 4-7). An acceleration voltage of 5 kV was used for imaging. Energy-dispersive x-ray spectroscopy at an acceleration voltage of 15 kV was used for compositional analysis. The filter sample was primarily composed, by weight, of oxygen, silicon, aluminum, and iron (Figure 4-8). Additional preliminary filter characterization using a Wood's metal intrusion technique was attempted and is described in Annex C.

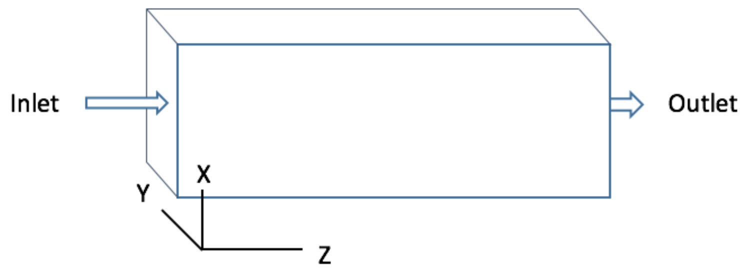


Figure 4-6: Orientation of the planes of the sample, viewing the through-thickness of the filter wall

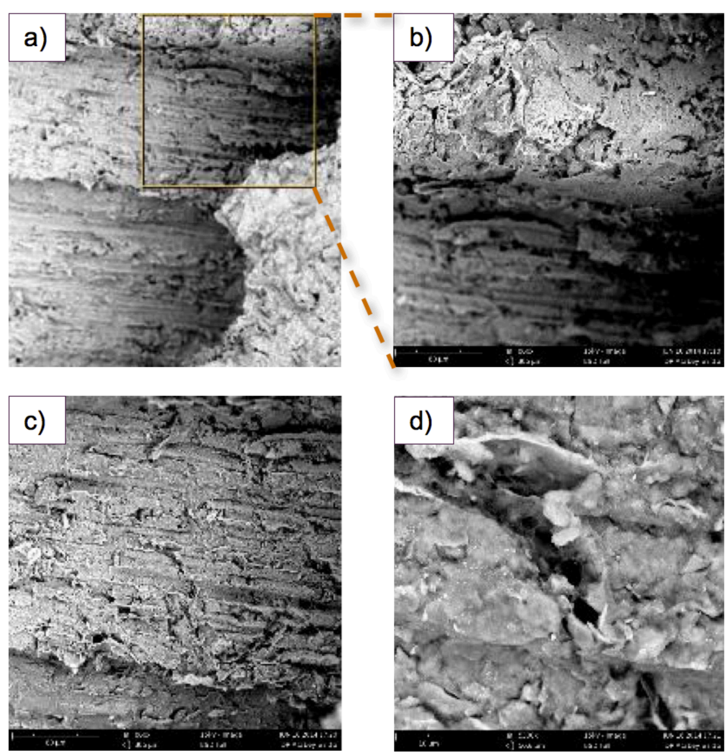


Figure 4-7: (a) Optical image; (b) BSE image at 600x; (c) BSE image at 1200x; (d) BSE image at 2000x

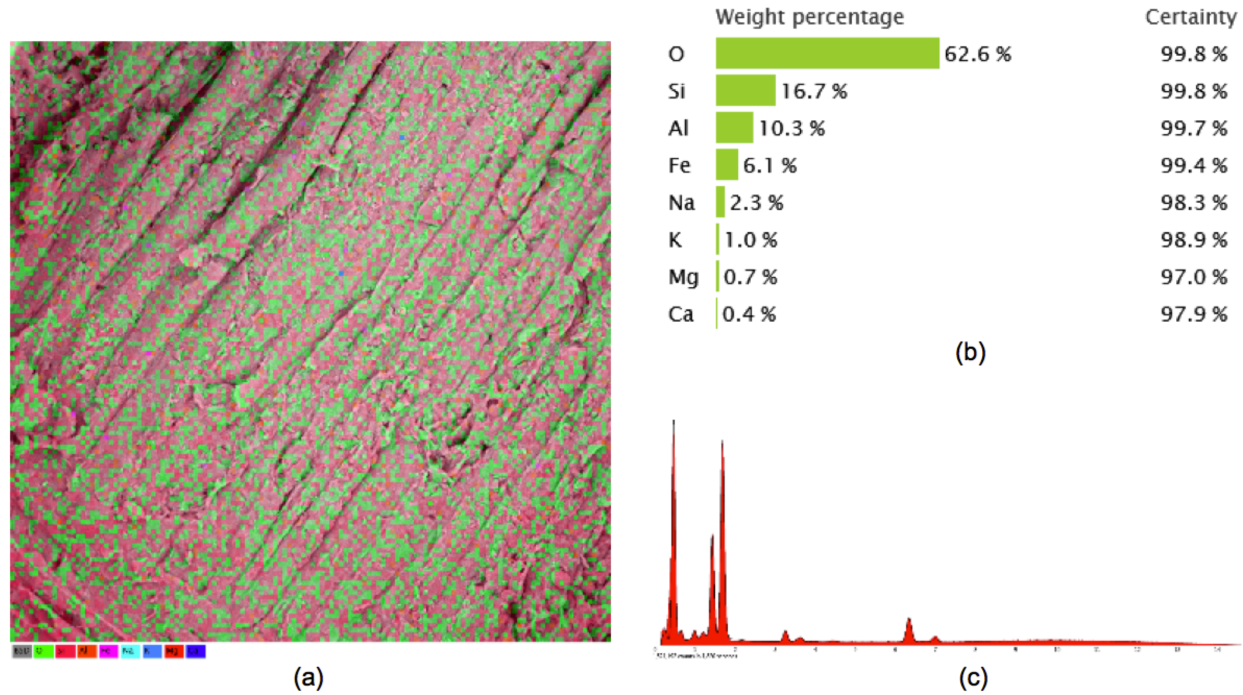


Figure 4-8: Compositional analysis of filter sample in SEM- (a) A backscatter electron and element combined image map: red (silicon), green (oxygen), orange (aluminum), magenta (iron); (b) Weight perecentage composition; (c) X-ray spectrum of sample.

4.2.4 Image Collection

The transmission of x-rays is related to the material properties by Beer-Lambert's law (Hawkes & Jackson 1980),

$$\frac{I}{I_0} = e^{(-\mu t)} \tag{1}$$

where I is the intensity of transmitted x-rays, I_0 is the intensity of the incident x-rays, μ is the liner attenuation coefficient for the material and is dependent on the material density ρ, and t is the thickness of the material in the direction of x-ray travel. The linear attenuation coefficient is related to the x-ray energy level by (Heismann *et al.* 2003),

$$\mu = \rho\alpha\frac{Z^k}{E^l} + \beta\rho \qquad (2)$$

where $\rho\alpha\frac{Z^k}{E^l}$ is the photoelectric absorption term, $\beta\rho$ is the Compton Scattering term, Z is the atomic number of the absorbing material, β is the scattering attenuation constant, and α is the photoelectric constant. Typical assigned values are k=3 and β = 0.02 m^2/kg when E<140 keV (Heismann *et al.* 2003); l=3.1 (Cho & Arthur 1975).

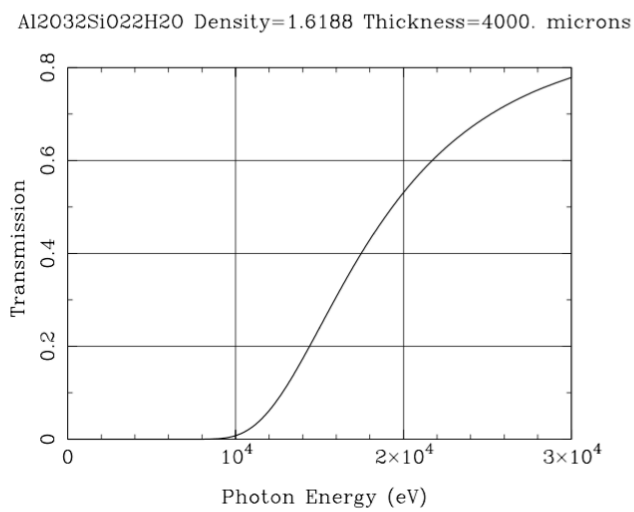


Figure 4-9: Transmission of alumina silicate sample (Henke 2017)

Using the data for a pure alumina silicate clay, $Al_2O_3(2SiO_2)(2H_2O)$ and assuming a sample is approximately 40% porous and 4000 microns thick, a curve for transmission (*I/I_0*) is generated over the range of possible photon energies from 10 eV – 30,000 keV using the filter transmission calculator from the Henke group at Lawrence Berkeley National Labs (Henke *et al.* 1993). Generally, an acceptable signal to noise ratio transmission of >60% is appropriate. Imaging conducted at 25 keV yields 70% transmission, which is acceptable (Figure 4-9). Increasing source energy or reducing sample thickness are two solutions to increase transmission.

Tomographic images were collected at both the Advance Light Source and the Advance Photon Source. At the Advance Light Source at Lawrence Berkeley National Labs, the samples were imaged on beamline 8.3.2. X-rays at the 25 keV frequency were selected using a double-multilayer moncromator. A 0.5 mm LuAG scintillator with 5x lenses and a sCMOS PCO edge camera were utilized for detection. This created a 3.3 mm horizontal field of view and 1.33 μm per pixel resolution. This resolution captures the macropores, which represent the engineered filter pathways, without crowding the resultant image with the micropores of the ceramic matrix. At the Advance Photon Source at Argonne National Labs, the samples were imaged on beamline 2-BM-A,B. X-rays at the 25keV frequency were selected using a double-multilayer monocromator. A 20 μm LuAG scintillator with 5x lenses and a sCMOS PCO edge camera were utilized for detection. This resulted in 1.33 μm cubic voxels and a horizontal field of view of 3.3 mm. Scans were performed over 180° of rotation resulting in 1500 projections. The exposure time was 50 ms and total scan time was 3 minutes.

The sample was mounted on the stage perpendicular to the detector (Figure 4-10). Two to four tomographic scans were taken along the through-thickness direction to encompass the entirety of the sample.

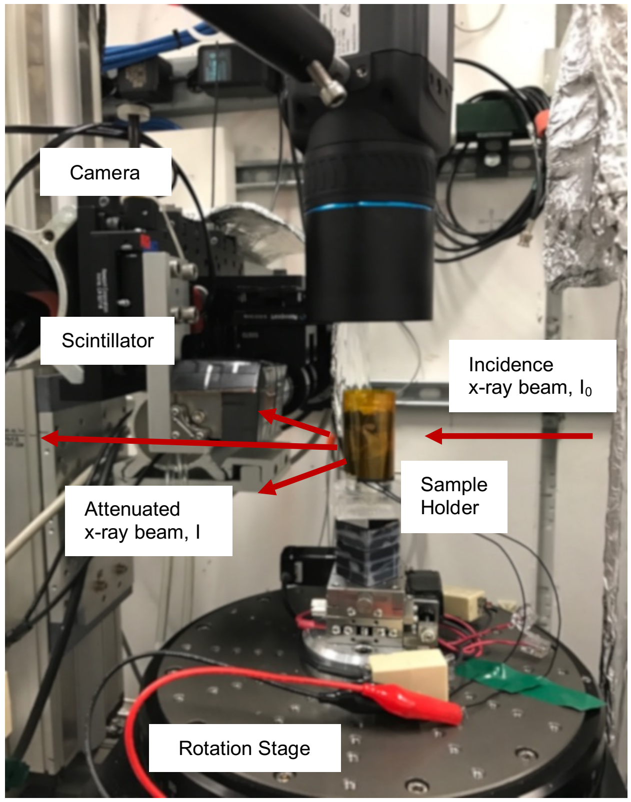


Figure 4-10: Image collection set-up in beamline

4.2.5 Image Processing

Samples were first reconstructed using TomoPy and then segmented by phase and processed in Fiji/ImageJ. For visualization purposes, 3D volumes were created using Avizo Fire 8.1.

Reconstruction Reconstruction consists of de-blurring of the sinogram, thereby resolving the image collected in an individual slice, which can be aligned to form a virtual image stack and can be viewed as an image volume (Figure 4-11). Reconstruction of the tomographic scans and phase retrieval (solid vs. void) was performed with TomoPy (Gursoy *et al.* 2014) using an open-source algorithm developed at Argonne National Laboratory (Xiao 2016), in a Linux environment on a 32 GB RAM workstation. A stripe reduction filter was used on the sinograms with the parameters 'ringSigma =3','ringLevel=8', and 'ringWavelet=db5' and a Butterworth filter was applied with parameters of 0.2 and 2. The ratio between the imaginary and real part decrement in the refractive index of the sample material was set to $1x10^{-4}$. The center of reconstruction was visually confirmed for each image sequence by checking the focus of a short stack prior to running the reconstruction algorithm on all image slices. The reconstructed image data was stored in .tiff format as an image stack.

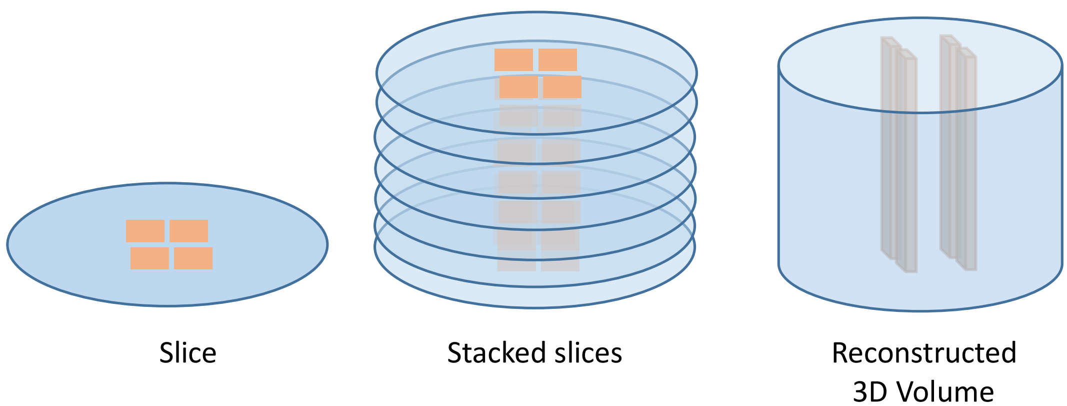


Figure 4-11: Reconstruction process

Stitching As the through wall thickness of the samples were tall, and required multiple CT, a final image sample required image stacks to be aligned and stitched together. Prior to concatenating stacks into one through wall sample, the stacks were matched by using features common to the last slice of the top stack and the first slice of the bottom stack. The slices were used in a translation plug-in in Fiji/ImageJ to determine the amount of x & y shift that the bottom stack needed to assure proper alignment. After concatenation, any overlapping regions in the z-plane were removed and the final through wall thickness image stack saved for further processing.

Downsampling Using Fiji/ImageJ the image stacks were first converted from 32-bit to 8-bit greyscale images, which linearly assigned each pixel a value from 0-255, thereby decreasing the file size of the image stack. As the image stack file sizes were large and the data contained in the reconstructions highly detailed, a downsampling algorithm was applied in 3D. The process of downsampling discarded some image data to reduce image noise and details, but did not compress the image. A 3D Gaussian blur was used as the convolution or smoothing filter on the greyscale image, with a sigma of 2.0 applied in the x,y, and z directions (Rasband 2012). The Gaussian filter is similar to the mean filter, but instead of using uniform weights, it uses the weights of a normal (Gaussian) distribution, where sigma is the standard deviation of the distribution (Dogra & Bhalla 2014). This blur was chosen as it preserves boundaries and edges better than other mathematical filters. Images pre- and post-downsampling were visually checked and porosities compared to ensure that over-smoothing had not occurred.

Thresholding A useful imaging technique is to partition a sample into material types based upon the intensity of the attenuated x-rays. To segment the image into material classes, a global thresholding is applied using the Otsu technique (Otsu 1979). Validation of the Otsu method was performed by manually thresholding an example image as well.

Thresholding on a grey scale image is applied by finding the maximum of the inter-class variance between the two materials (Otsu 1979),

$$\sigma_b^2(t) = \omega_o(\mu_o - \mu_T)^2 + \omega_1(\mu_1 - \mu_T)^2 \tag{3}$$

where the variance, σ_b, of the threshold, *t,* is defined by the normalized weights of the two classes, $\omega_{o,1}$, the means of the classes, $\mu_{o,1}$, and the total mean intensity of the image, μ_T. The resultant image stack was separated into ceramic material, thresholded as white (RGB value 255), and porous voids, thresholded as black (RGB value 0). The histogram of the thresholds were exported and saved. The resultant image stack was converted to binary using the Fiji/ImageJ plug-in and saved.

Morphological Opening Lastly, an opening technique was utilized to simplify the shapes in the binarized structure by removing morphological noise via the processes of eroding then dilating in 3D. Each slice of the reconstructed image was treated as a binary matrix to which a smaller dilatation matrix was applied (Figure 4-12). The process of erosion consists of superimposing a kernel (Matrix B) to every pixel of the image (Matrix A), and if any of the pixels in the kernel are part of the background, the pixel under the center of the kernel turns to the background (Serra & Vincent 1992). Dilatation is the opposite process, where the center of the kernel turns to the foreground value if any of the pixels inside the kernel are part of the foreground. To extend this methodology to 3D, a cubic or 3D ellipsoidal kernel is used.

The process of opening involves first applying the erosion operation to remove small spots in the background and then to dilate the pixels back to their original color. The counter process, closing, involves first dilating then eroding to fill holes inside of foreground objects. For the ceramic filter samples, the 3D erosion process was applied seven times to close small pores associated with the ceramic matrix, and the 3D dilatation procedure was applied seven times to return the pixels to their initial color. Images pre- and post-opening were visually checked and porosities compared to ensure that over-filtering had not occurred.

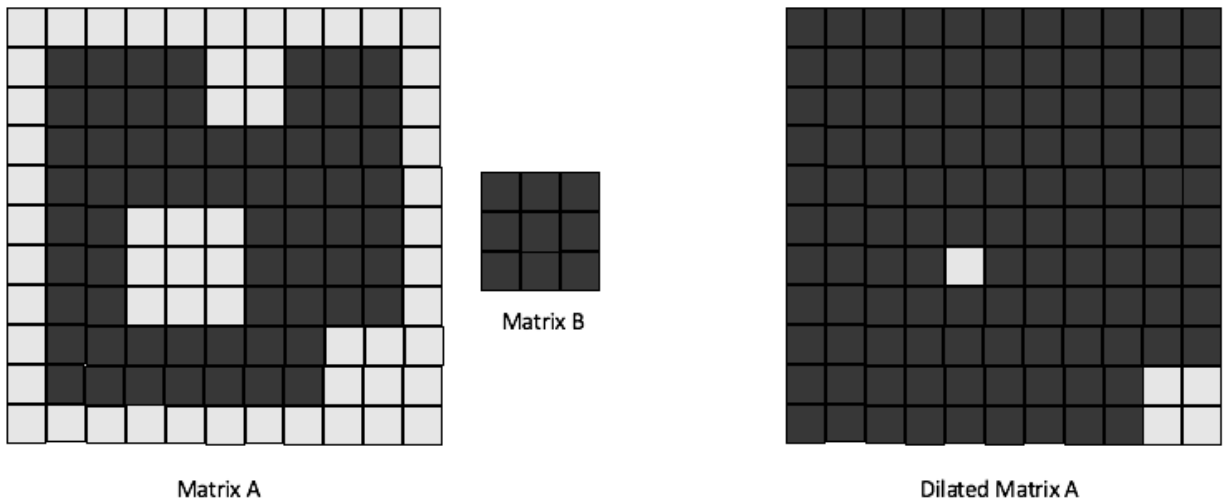


Figure 4-12: 2D erosion procedure on an example binary matrix, dilatation results in expanded white sections.

Ellipsoid Factor The image stack for each sample was subdivided into 25-39 smaller stacks (based on a subdivision stack target size of ~250MB) in the ZX direction, to allow for further processing (Figure 4-13). These subdivision stacks were processed on 22 12GB RAM computers concurrently. A duplicate image stack of each sample was created to be processed in the *Ellipsoid Factor* plug-in in *BoneJ* in Fiji/ImageJ (Doube 2015). The ellipsoid factor process seeds ellipsoids into voxels in the pore space. The process runs iteratively using a combination of dilation, contraction, rotation, and translation until the ellipsoid seed can no longer increase in volume.

An ellipsoid image stack was the output of the routine, consisting of a map of ellipsoids where the color corresponded to the ellipsoid factor. This image stack was then thresholded to a binarized image stack; this smoothed and approximated the pores as ellipsoids (Figure 4-14). The binarized stack was then used in the *Particle Analyzer* routine in Fiji/ImageJ for morphological characterization. In combination, the *Ellipsoid Factor* and *Particle Analyzer* routines took approximately 12 hours to process per subdivision.

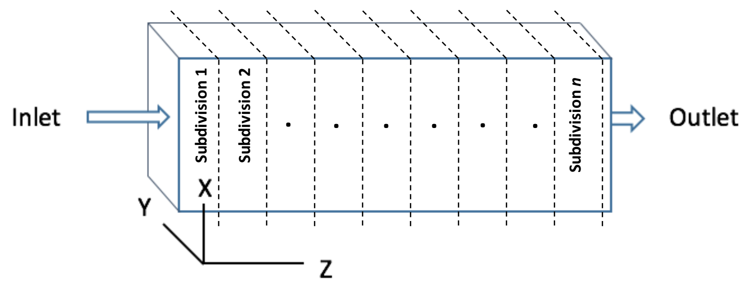
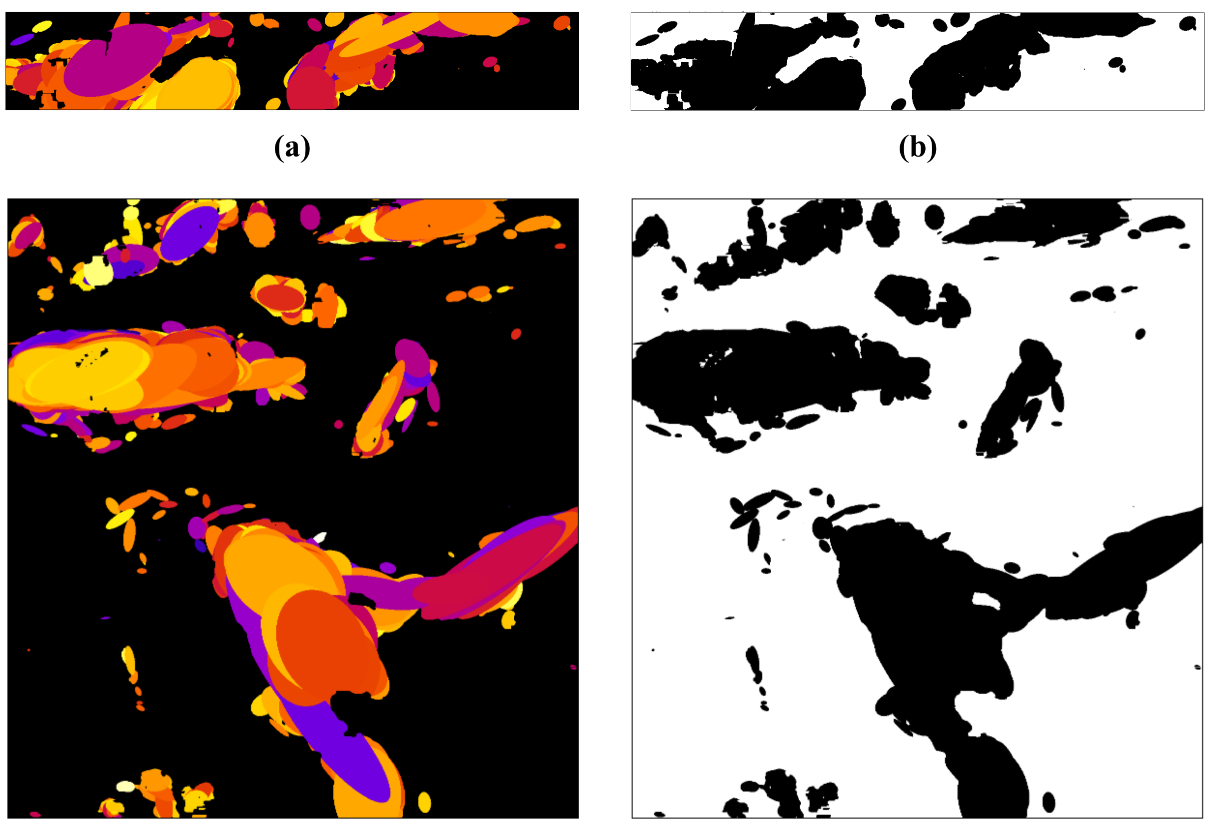


Figure 4-13: Subdivisions for Ellipsoid Factor and subsequent Particle Analyzer routines



(a) (b)

(c) (d)

Figure 4-14: Ellipsoid factor routine in preparation for morphological analysis. (a) ZX ellipsoids fitted into pores; (b) ZX threshold of ellipsoid fitted pores; (c) YX of ellipsoids fitted into pores; (d) YX threshold of ellipsoid fitted pores.

4.2.6 Morphological Characterization

Morphology of the ceramic filter samples was described by porosity, pore size distribution, tortuosity, and form factor.

Porosity Porosity is the fraction of void space of a material and is defined as

$$\phi = \frac{V_V}{V_T} \tag{4}$$

where V_V is the volume of the void space, represented in black in the resulting images and V_T is the total volume of the sample. Porosity was calculated in Fiji/ImageJ using the binarized histogram. Through-plane porosity in the ZX and YX directions of both the original and opened samples were also computed using a custom ImageJ macro (Serov *et al.* In process). All porosity measurements were conducted on the full-sample, not on the subdivision stacks.

Pore Size Distribution The pore size distribution was calculated on the ellipsoid factor binary image subdivision stacks via the *Particle Analyzer* plug-in in *BoneJ* for Fiji/ImageJ. *Particle Analyzer* relies upon another native Fiji/ImageJ plugin, *Local Thickness*, to extract the size distribution of the pores. The local thickness of the pore is the diameter of the maximal sphere that is inscribed inside the void (Hildebrand & Rüegsegger 1997). A histogram of pore radii is plotted against the power density function (PDF) of the counts of occurrence of the radii (Zenyuk *et al.* 2016; Zydney *et al.* 1994).

$$PDF(r) = \sum_{k=1,2} f_{r,k} \left\{ \frac{1}{r\sigma_k \sqrt{2\pi}} exp \left[- \frac{(\ln r - ln\, r_{0,k})^2}{2\sigma_k^2} \right] \right\} \tag{5}$$

where *PDF(r)* is the normalized volume of pores with radius *r*, $f_{r,k}$ is the fraction of pores encompassing the distribution *k*, where $r_{0,k}$ is the characteristic radius and σ_k is the spread of the distribution *k.*

Tortuosity Tortuosity is an important parameter in porous media flow, and is typically used in transport as a flow retardation parameter. First modeled by Carman, and extended to a bed of packed spheres by Epstein, tortuosity is derived from the modification of the Hagen-Poiseuille equation for pressure drop through a tube (Carman & Stein 1956; Epstein 1989). Fluid flowing through a tube that is torturous travels along a longer length path than the overall thickness of the matrix through which it is flowing, therefore tortuosity, τ, is represented by

$$\tau = \frac{L_e}{L} \tag{6}$$

where L_e is the effective length of the fluid path and L is the thickness of the matrix. Tortuosity is often expressed in it's squared form, as the tortuosity factor κ.

$$\kappa = \tau^2 \tag{7}$$

The tortuosity factor and conductive volume fraction were calculated using *TauFactor*, a Matlab application that accepts image based microstructural data on a flux-based algorithm (Cooper *et al.* 2016). TauFactor applies a concentration gradient to a 3D matrix of binarized values representing the solid and void space of the image and iteratively calculates the diffusive flux until convergence. The diffusive flux value is the utilized to solve for the tortuosity factor, κ

$$(D_A)_{eff} = \frac{\varepsilon}{\kappa} D_A \tag{8}$$

Due to the colossal size of data in the sample image sets, samples were divided into 4-7 sections in ZX, and those were individually processed for flow in the through plane direction. Due to the size and memory requirements to process each section, *TauFactor* was run from the command line on the Tufts University Research Cluster on the large memory node. Cluster parameters for job submission included: 5-day runtime, 12 CPUs, and 100 GB RAM.

Formation factor The formation factor, F, is a ratio of the tortuosity to the porosity (Suman & Ruth 1993). For this comparison, the volume fraction data collected simultaneously with the tortuosity factor from *TauFactor* was used for the porosity to minimize error that may occur between different determination methods. The square root of the tortuosity factor was calculated to represent tortuosity. The formation factor for each section and for each sample was plotted for comparison.

Ellipsoid Factor Ellipsoids are characterized by their major, intermediate, and minor axes, and can be related to each other through a measure known as the ellipsoid factor (EF)

$$EF = \frac{a}{b} - \frac{b}{c} \tag{9}$$

where a, b, c are the lengths of the ellipsoid axes such that length of a < b << c. EF values will range from -1, oblate, to 0, spherical, to 1, prolate. Further the axial ratios (a/b) and (b/c) can be plotted to visually represent the shape of the ellipsoids. Ellipsoids were calculated in Fiji/ImageJ using parameters for the *Ellipsoid Factor* routine: sampling increment of 0.435 μm, 100 vectors, 50 skeleton points, contact sensitivity of 1, maximum number of iterations at 100, maximum drift of 1.73205 μm. The *Particle Analyzer* routine calculated values for a, b, and c. Additionally, the *Anisotropy* routine from *BoneJ* was performed on the ellipsoids to calculate the fabric tensors and degree of anisotropy for each sample in the ZX and YX directions.

Figure 4-15: Falling head test experimental set-up

Experimental Flow Rate Measurement of flow rates were conducted on filters C and D prior to cutting samples out for imaging via falling head tests. Following standard methods, filters were fully submerged in tubs of tap water for 24 hours to ensure no air remained trapped in the pores and the filter had reached full saturation (Nederstigt & Lam 2005). Then filters were mounted on a custom stand above a collection receptacle that was sitting on a mass balance (Figure 4-15).

Filters were filled to the rim with tap water, covered to prevent evaporation, and allowed to drain to empty. The balance recorded the mass of filtrate every ~60 seconds and the head height of water was recorded using a custom T-square at intervals over the course of the test.

Pore Network Model Development Experimental data collected from falling head tests on Filters C and D were used to extract permeability constants. These constants were then compared to permeability constants of the network extraction model. The network extraction model was then used in OpenPNM for both a mercury intrusion porosimetry and filtration model (Bear 1972; Gostick *et al.* 2016).

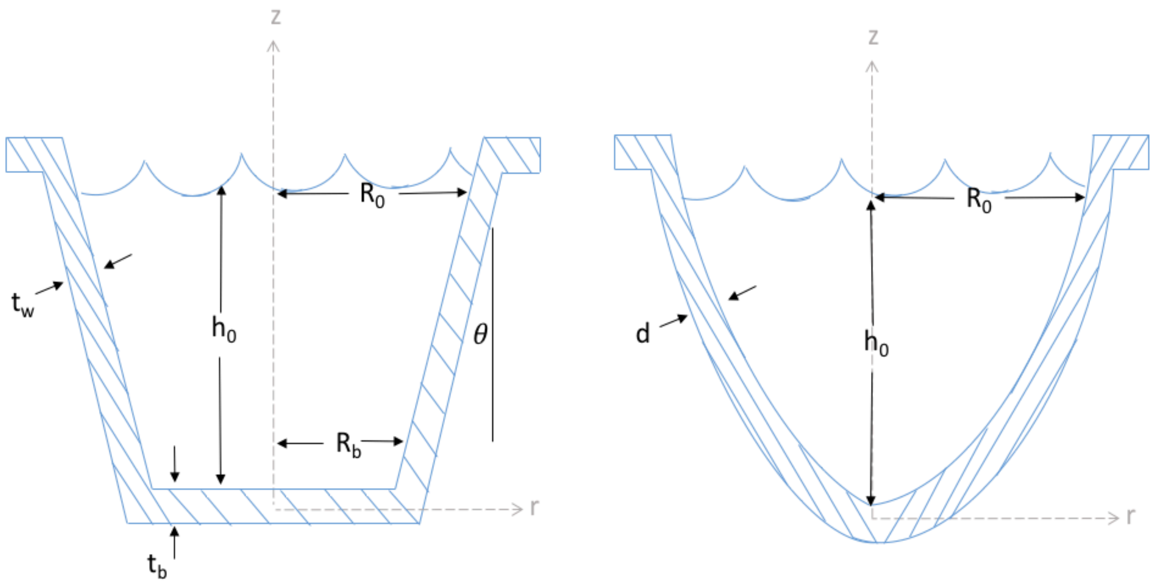
Flow Modeling Ceramic filter properties for Filter C and D were measured in the laboratory and utilized in the equations for flow modeling (Figure 4-16). Flow rate through the ceramic water filters can be modeled using Darcy's Law (Bear 1972),

$$Q = \frac{-kA}{L\mu}\Delta p \tag{10}$$

where Q is flow rate (m/s), k is the permeability constant (m^2), A is the area of the filter surface (m^2), L is the through-thickness of the filter wall (m), μ is the dynamic viscosity of water (Ns/m^2), and Δp is the change in pressure (N/m^2). The change in pressure can be modeled as

$$\Delta p = \rho g(h_0 - h) \tag{11}$$

where ρ is the density of water (kg/m^3), g is acceleration due to gravity (m/s^2), and h is the height of water (m). The flow rate is dependent on the head height, which is a function of time.



(a) **(b)**

Figure 4-16: (a) Frustum shaped filter (Filter C); (b) Paraboloid shaped filter (Filter D)

For the frustum shaped filter, following procedures similar to Schweitzer et. al (2013) and Annan et. al (2014) equations are derived as follows. First, the radius is a function of height

$$r = R_b + ztan(\theta) \tag{12}$$

where R_b is the radius of the base and θ is the interior angle of the filter wall from the base. Flow through the filter wall is

$$Q_w(t) = \frac{\pi k \rho g h(t)}{\mu t_w}\left[R_b h(t) - \frac{\tan(\theta)\, h(t)^2}{3}\right] \tag{13}$$

where *h(t)* is the instantaneous head height, and t_w is the thickness of the wall. Flow through the filter base is

$$Q_b(t) = \frac{\pi k \rho g R_b^2 h(t)}{\mu t_b} \tag{14}$$

Combined, the flow rate through a frustum shaped filter is

$$Q(t) = \frac{\pi k \rho g h(t)}{\mu}\left[\frac{R_b^2}{t_b} + \frac{R_b h(t)}{t_w} + \frac{\tan(\theta)[h(t)]^2}{3t_w}\right] \tag{15}$$

The mass flow rate is the first derivate of the volumetric flow rate, which is related to the change in height over time by

$$\frac{dV}{dt} = -\pi r^2 \frac{dh}{dt} \tag{16}$$

$$\frac{dh(t)}{dt} = -\frac{\rho g h(t)}{\mu} \frac{\left[\frac{R_b^2}{t_b} + \frac{R_b h(t)}{t_w} + \frac{\tan(\theta)[h(t)]^2}{3t_w}\right]}{[h(t)]^2 tan^2(\theta) + 2R_b h(t)\tan(\theta) + R_b^2} \tag{17}$$

Substituting eq. 17 into eq. 16 and solving for the change in height results in

$$V(t) = \pi R_b^2[h_0 - h(t)] + \pi R_b \tan(\theta)\{h_0^2 - [h(t)]^2\} + \frac{\pi}{3} tan^2(\theta)\{h_0^3 - [h(t)]^3\} \tag{18}$$

EQN 8 cannot be integrated and must be solved for numerically at each time step; both Explict Euler and 4th order Runge-Kutta methods were utilized in Matlab, via an in-house routine and ode45 respectively.

For the paraboloid shaped filter, following a procedure laid out by Schweitzer et. al. the flow rate is modeled again under Darcy's Law as (Schweitzer *et al.* 2013)

$$Q = \frac{kA\rho g[h(t) - z]}{\mu d} \tag{19}$$

where it is assumed that the filter is a uniform thickness, *d.* A relationship is needed to describe the surface area of the paraboloid that will be integrated over, therefore a function for changing radius with changing height, *z*, was developed

$$r = az^n \tag{20}$$

where *a* and *n* are shape factors describing the parabola, similar to the definition of a standard parabola of $y=cx^2$. The flow rate is solved for by integrating across the surface area, dA, which can be further broken into an integral over dθdz.

$$Q = \frac{k\rho g}{\mu d} \int_0^{2\pi} \int_0^h (h - z) r d\theta dz \tag{21}$$

and can be integrated to solve for the flow rate at any given height

$$Q = \frac{2\pi a k\rho g}{\mu d(n + 1)(n + 2)} h^{n+2} \tag{22}$$

Using the relationship between changing head height and changing volume, eq. 16, and substituting eq. 20 for radius, the head height can be found from a separable differential equation

$$h(t) = \left[h_0^{n-1} + \frac{2kt(1 - n)}{ad(n + 1)(n + 2)}\right]^{\frac{1}{n-1}} \tag{23}$$

and the filtered volume at any point in time to be the initial volume of water in the filter minus the volume corresponding with head height at time, *t*

$$V(t) = \frac{\pi r_0^2 h_0}{2n+1}\left\{1 - \left[1 + \frac{2\rho g(1-n)h_0 t}{\mu(n+1)(n+2)r_0 d}\right]^{\frac{2n+1}{n-1}}\right\} \tag{24}$$

Measurements from Filters C and D were used as parameters to model both the head height and flow rate and were plotted over the drainage time. This was plotted against the experimental data for both filters. The permeability constant was adjusted in the models until the sum of squares error in the head height and flow rate plots was minimized in comparison to the experimental data.

Pore Network Extraction The black and white processed image stack was utilized in a Python proprietary algorithm (Gostick, 2017) where the pores and connecting throat areas were modeled as spheres and cylinders via an improvement on the maximal ball extraction method. The larger pores were fitted with spheres of a larger diameter. The networks were visualized using the open source Paraview software.

Pore Network Model The extracted network is utilized in the open source Python based program OpenPNM to calculate morphological properties of the network. For the purposes of this dissertation, only the pore and throat size distributions will be presented.

4.3 Results

A method of imaging and image processing filter samples utilizing an X-ray micro-CT, reconstruction algorithms, ImageJ/Fiji, and TauFactor was developed. Overall, 100 through-thickness ceramic filter samples were prepared for imaging. Of those samples, 8 were randomly chosen for imaging at ALS and 19 were randomly chosen for imaging at APS. After evaluating the reconstructions for completeness, four samples (one each from Filter A-D) imaged at APS were selected for image processing and morphological study (Figure 4-17-Figure 4-20). For ellipsoid factor and PSD analysis, filter A was divided into 39 sections, filter B was divided into 25 sections, filter C was divided into 36 sections, and filter D was divided into 27 sections. These filter samples were utilized to validate the developed method and the morphology of the pores was characterized as an example of the method. Additionally, preliminary data from a pore network model of the samples was collected and further use of this methodology was proposed.

Volume renderings of the pore space (i.e. producing a mesh such that the void space appears solid and the clay solid is invisible) of each filter allow several high-level observations (Figure 4-17-Figure 4-20). Filter C had a rice hull burn-out material, hence the visually observed pores are elongated in the x-direction, which is normal to the direction of applied force during molding of the filter. Filters A, B, and D had a sawdust burn-out material, that took on slightly different pore shapes depending upon filter. Also observable is that pore-formers in Filters B and D were smaller and more uniform throughout the samples, while the pores in Filter A were larger and more disconnected.

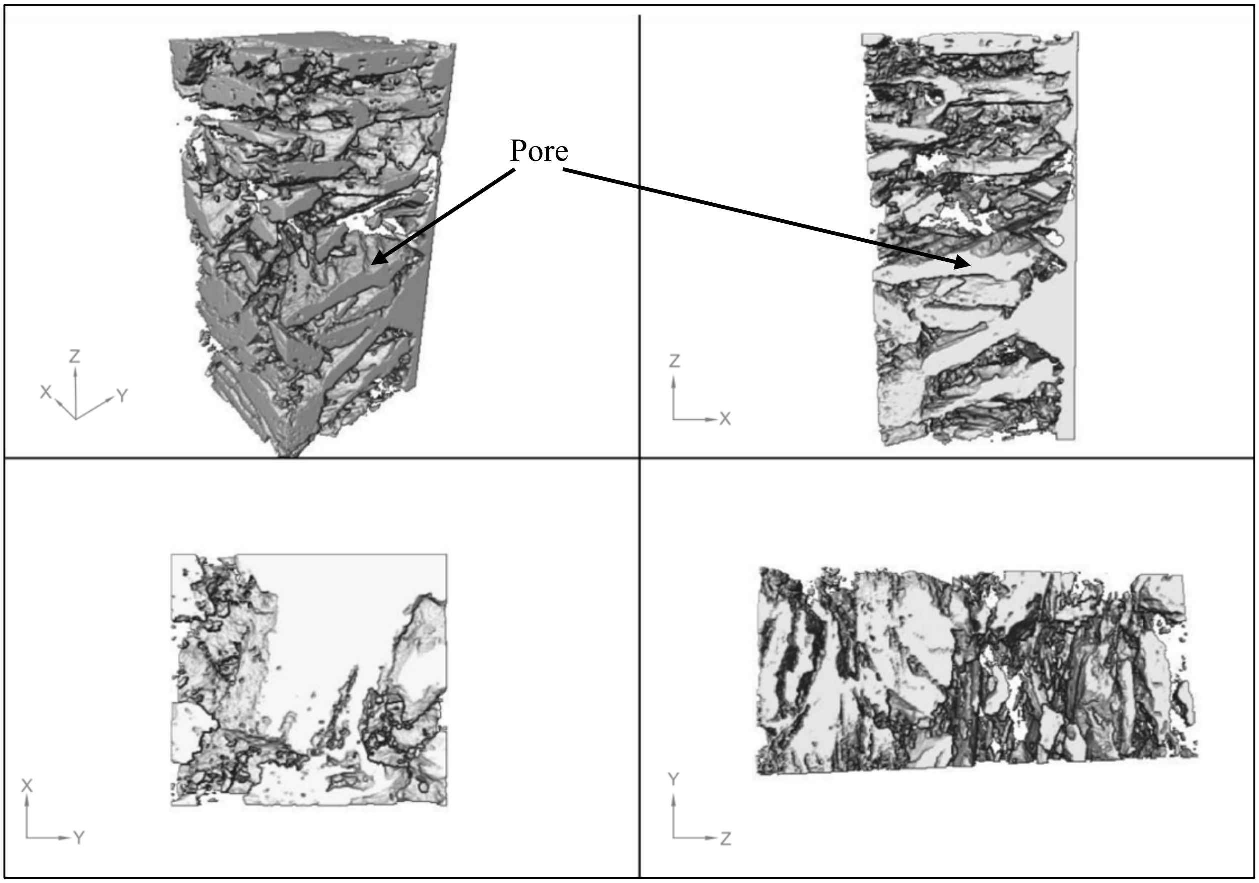


Figure 4-17: Three-dimensional volume rendering of Filter A as viewed from different locations

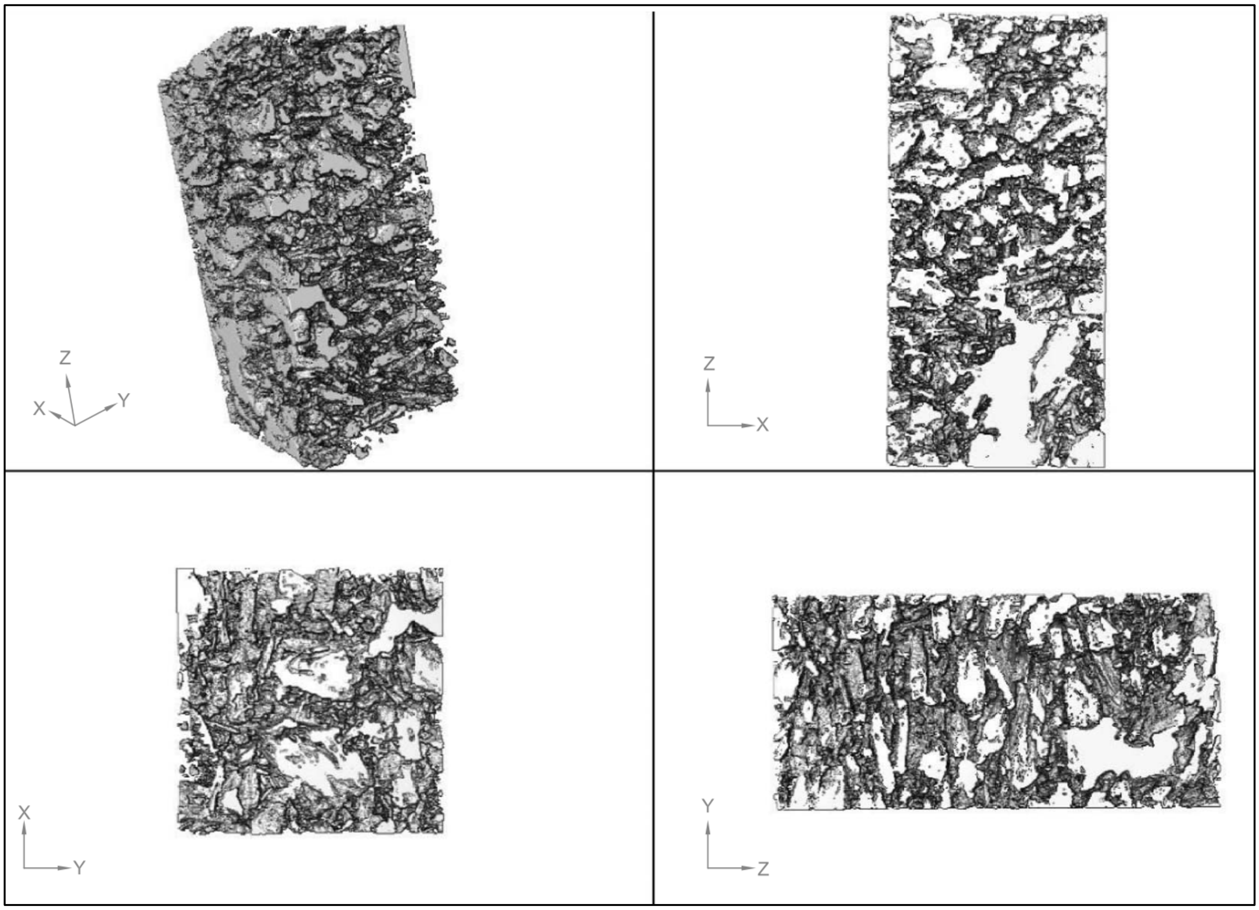


Figure 4-18: Three-dimensional volume rendering of Filter B as viewed from different locations

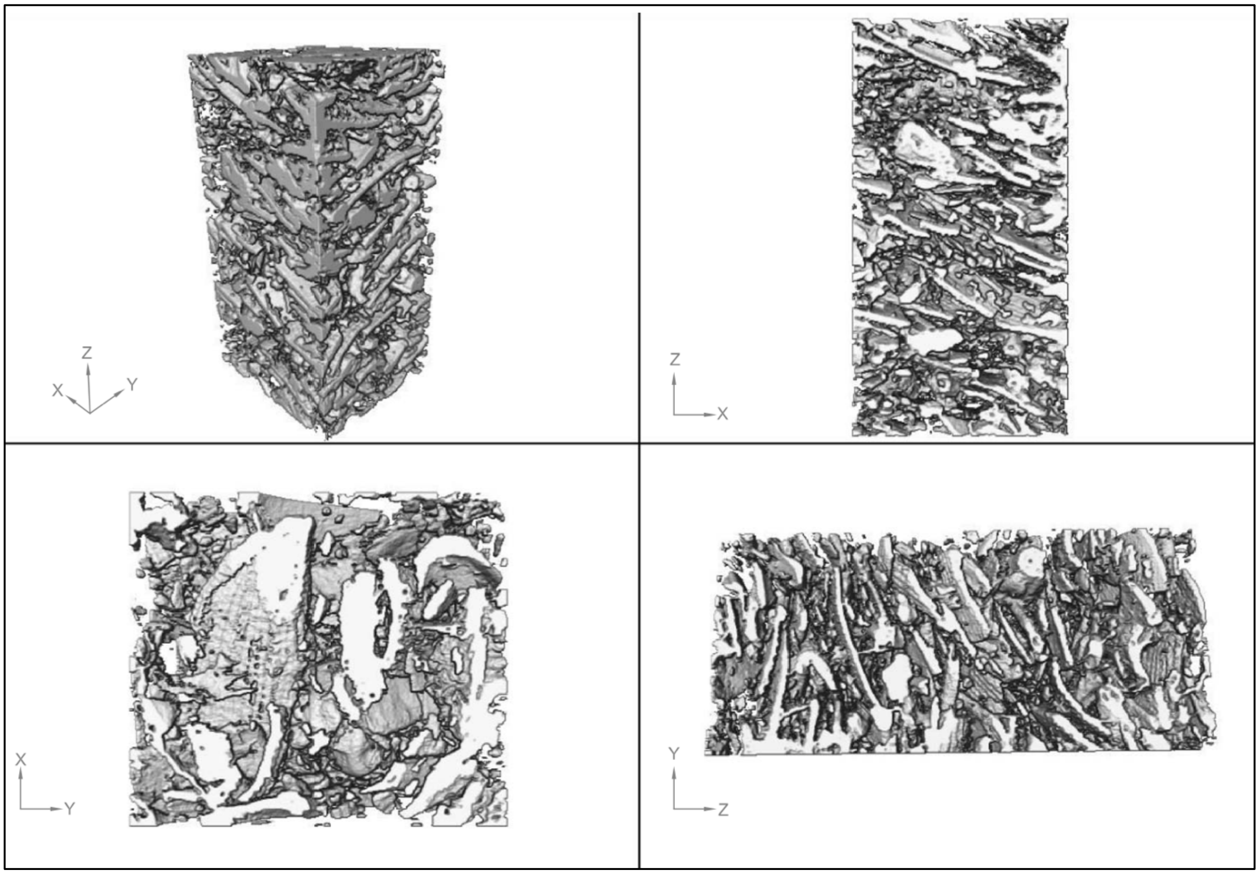


Figure 4-19: Three-dimensional volume rendering of Filter C as viewed from different locations

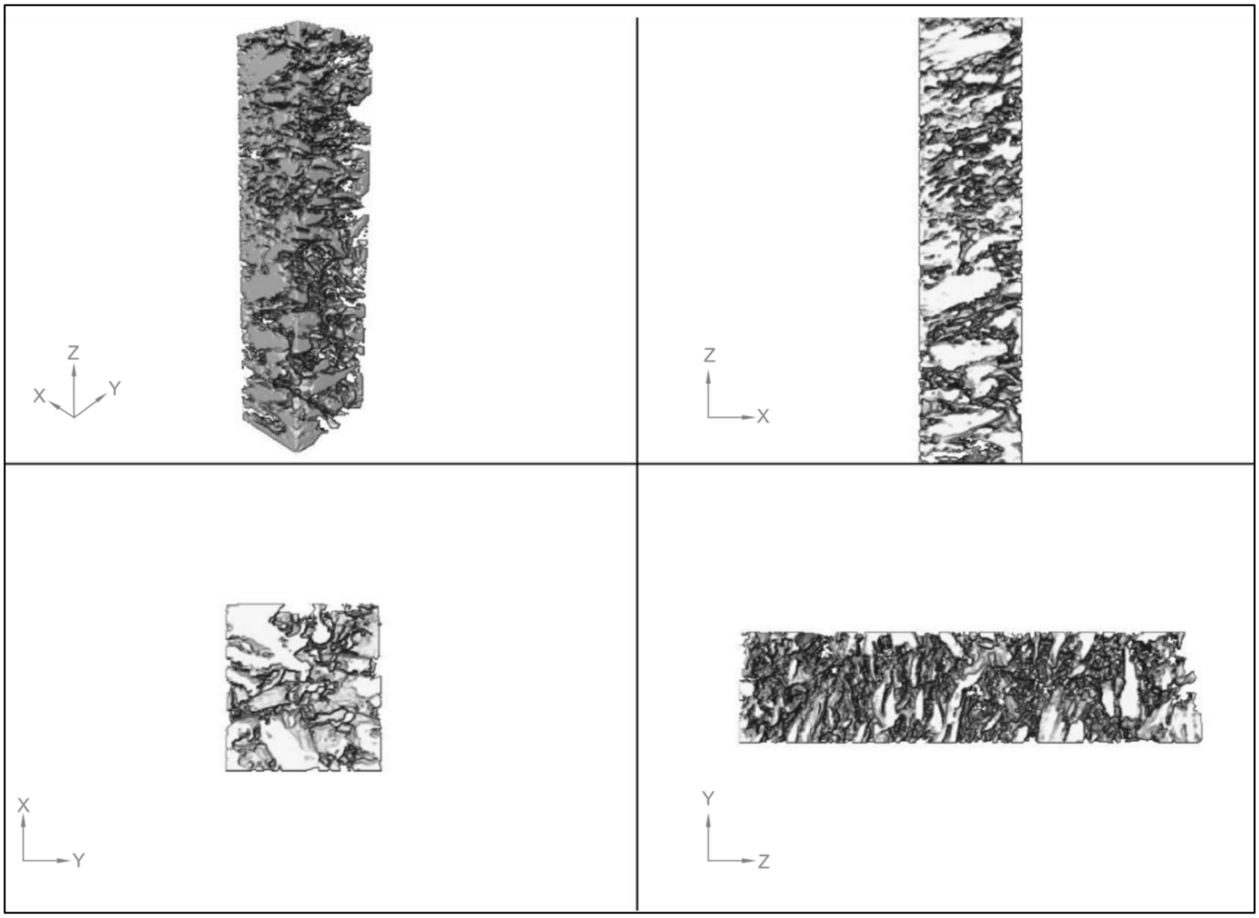
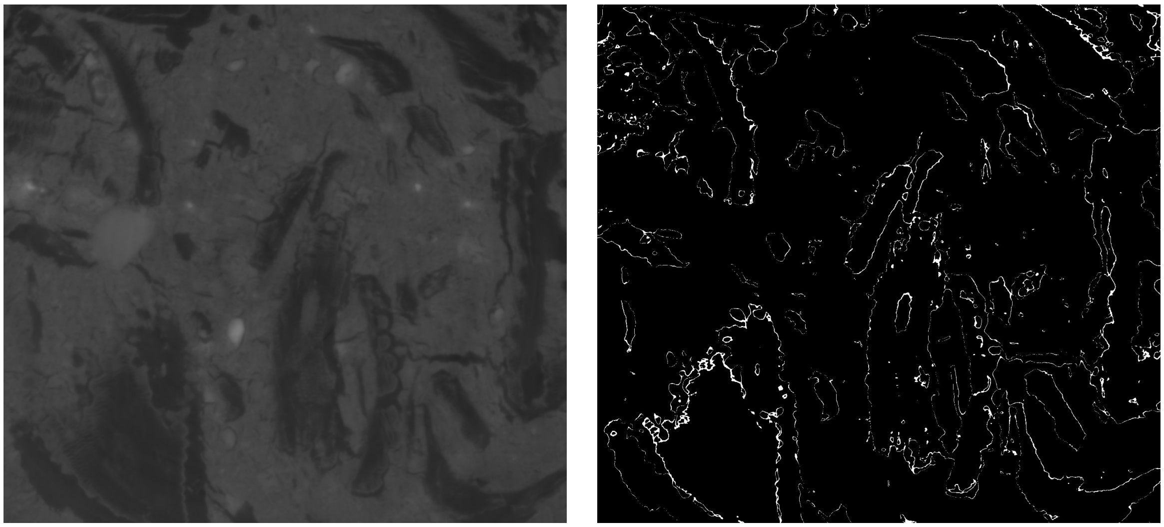


Figure 4-20: Three-dimensional volume rendering of Filter D as viewed from different locations

4.3.1 Image processing validation

Gaussian Blur validation on example image The porosity of the original greyscale stack was 36.8% and after the 3D Gaussian Blur was applied, the porosity was 38.6%. To visualize the effect of this removal, a calculation on the percent of solid that was sampled out of the image as a result of the blur was conducted, revealing percent solid removed was 3.3% (Figure 4-21). Predominantly the edges of the pores became more defined.



(a) **(b)**

Figure 4-21: Result of 3D Gaussian Blur: (a) Original; (b) Solid that was sampled out, represented in white

Thresholding validation on example image A comparison of a manual threshold of the greyscale image was used to validate the use of the Otsu threshold (Figure 4-22). The Otsu algorithm chose to threshold on an RGB value of 94; a manual threshold value of 84 RGB was chosen for comparison. The resulting porosity of the Otsu image was 0.433 and of the manually thresholded image was 0.357. The Otsu threshold resulted in more small pores than the manual threshold; however, as these small pores were later removed from the sample via imaging, an Otsu algorithm was deemed to be valid for application.

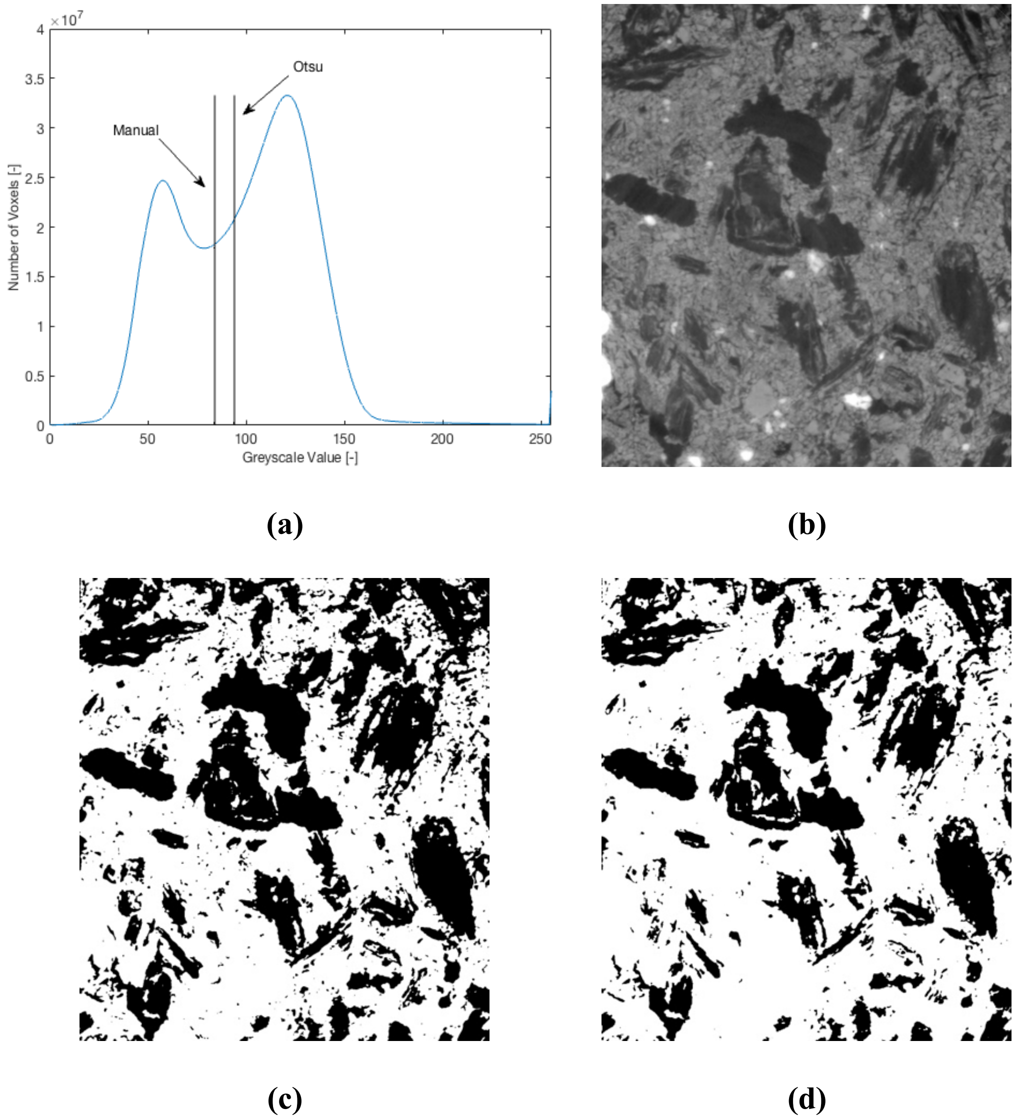
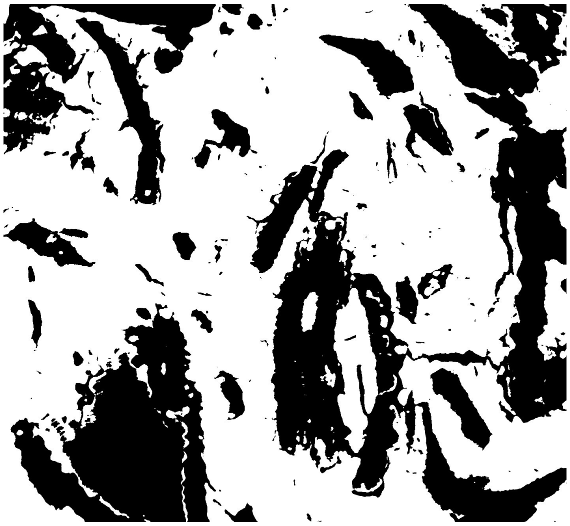


Figure 4-22: Threshold comparison - (a) Histogram of greyscale image; (b) Original greyscale image; (c) Result of Otsu thresholding algorithm; (d) Result of manual threshold

Opening procedure validation on example image The opening procedure decreased the porosity of the first slice from 38.6% to 35.5%, primarily through the removal of small matrix pores (Figure 4-23).



(a)

(b)

(c)

Procedure	Percent Porosity
Starting Image, porosity of slice	38.6%
3D Erode 7 times, porosity of slice	26.7%
3D Dilate 7 times after erode, porosity of slice	35.5%
After opening, porosity of stack	30.3%

(d)

Figure 4-23: Validation of the opening procedure: (a) Gaussian blurred starting image; (b) Erosion procedure; (c) Dilation procedure; (d) Porosity table

Validation of ceramic filter samples The procedures and validations presented in 4.4.1 confirmed the use of the chosen imaging techniques for processing the ceramic filter samples. Porosity was used to investigate the effect of all of the image processing in total, compared to the original samples. As expected, original samples always had higher porosity than the processed samples (Figure 4-24). The largest average difference between original and opened samples was for Filter

B at 8.6%. Filters A and C had an average difference of 1.8% and 1.9% respectively, and Filter C had an average difference in porosity of 3.6%. As these differences were <10% the image processing techniques were deemed reasonable.

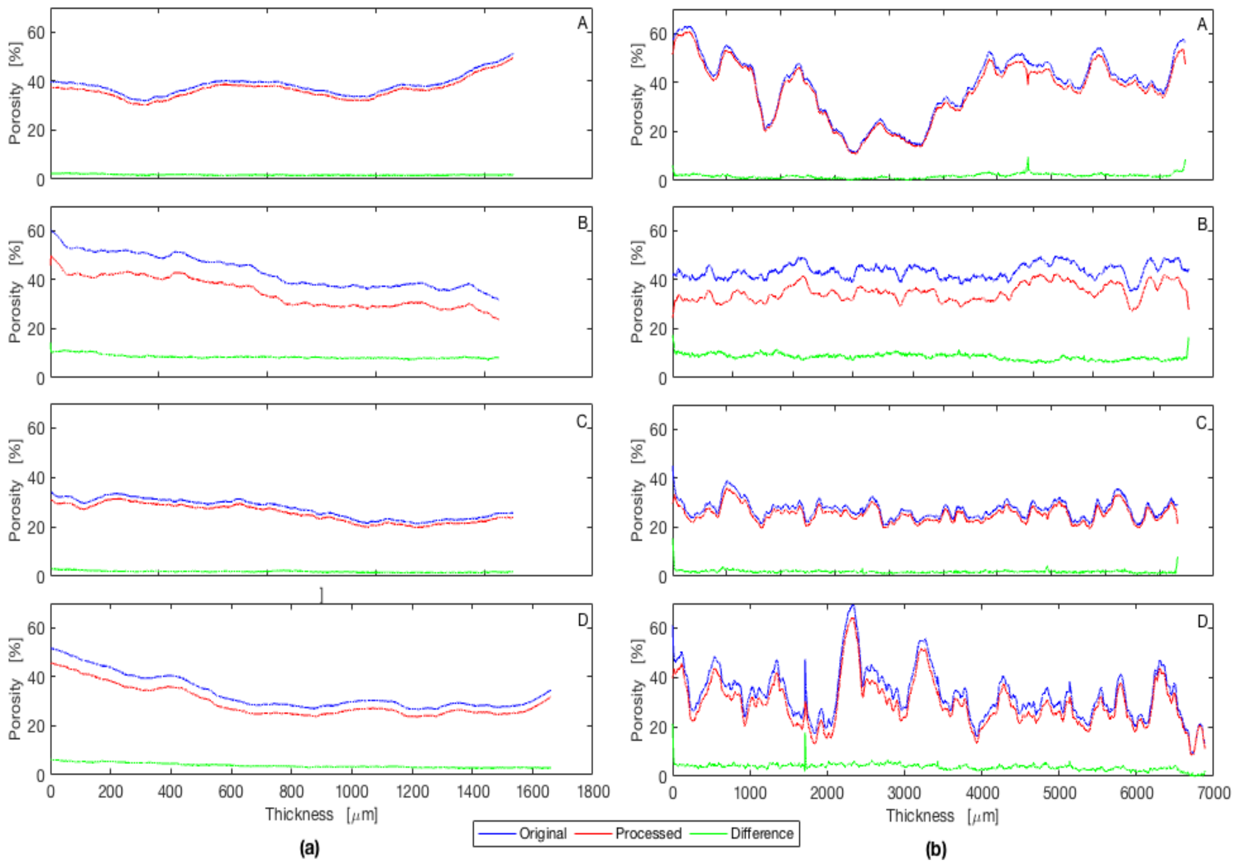


Figure 4-24: Comparison of porosities between original (blue) and opened (red) samples with the differences plotted (green)

4.3.2 Porosity

The porosity of the entire through-thickness processed sample was 36.54% for Filter A, 34.85% for Filter B, 25.52% for Filter C, and 29.52% for Filter D. Comparison of porosities between filters shows much overlap; generally, Filter C had the lowest porosity and Filter A and B had the highest porosities at different thicknesses (Figure 4-25). Filter C generally had the lowest and most consistent porosity across the thickness of the sample and was also the only filter made with rice hulls. Observing porosity in various plains it is evident that the most uniform porosity is in ZX plane. This indicates that the thickness of the sample selected for X-ray CT imaging was representative. The large variations in YX porosity for Filter A and Filter D (from 60 % at the edge to 10% in the middle) can be an indication of poor connectivity in the middle of the filter, and large tortuosity. From a manufacturing point of view, this could indicate that pore-formers were either not uniform or were not well mixed and evenly distributed. Filter B and Filter C showed the least variation in porosity, a possible indication of even distribution of pore-formers.

From the porosity profiles one cannot determine whether the porosity is mostly due to larger or smaller pores, or whether the pores are connected. Further, while maintaining some level of porosity is important to ensure that the filter produces water, porosity alone cannot give an indication about how effective the filter would be to removing contaminants from the water. A deeper look at the structure of the pores is important.

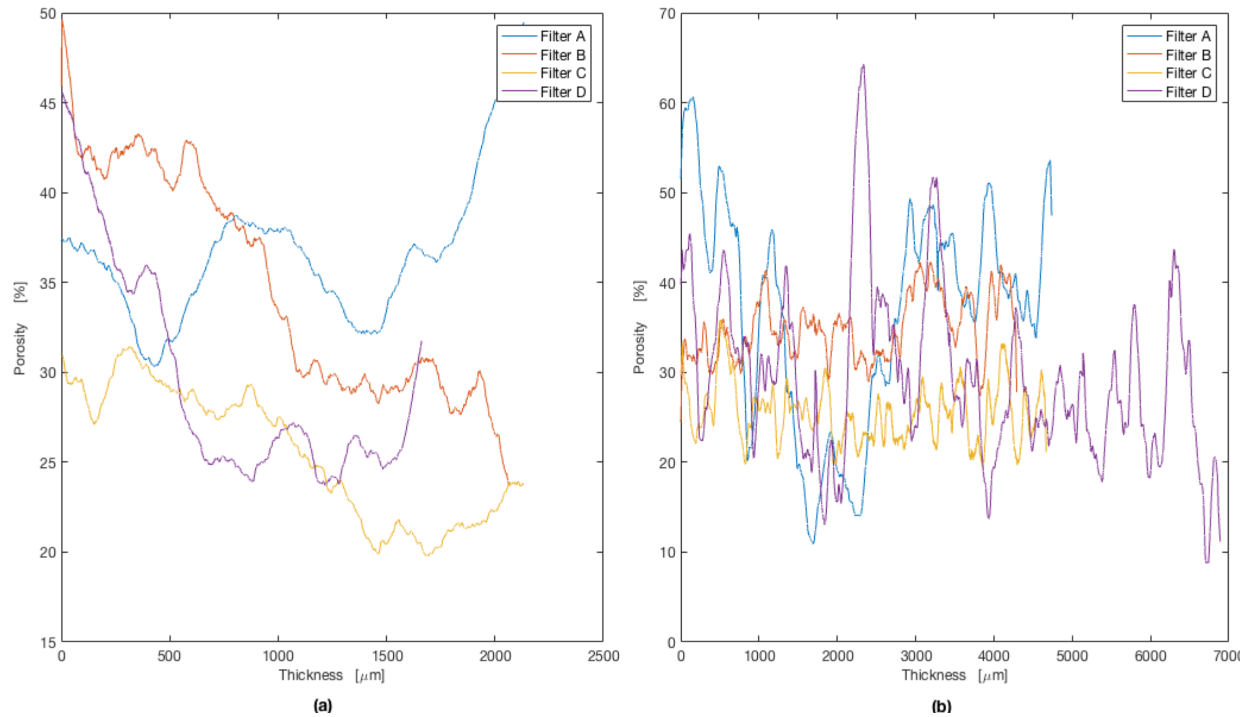


Figure 4-25: Comparison of all filter porosities through thickness of filter walls for ZX and YX directions

4.3.3 Pore Size Distributions

Due to resolution limitations, micro X-ray CT is not able to resolve meso and micro-pores that are below 1 μm. For this study, the minimum pore radius was 1 μm for all filters and the upper limits ranged from 80-120 μm, but have only been plotted up to 40 μm for visualization (Figure 4-26). Mean pore radius in each direction, ZX and YX; for all filters the bulk of pores were <15 μm (Table 4-2). By comparing PSDs in ZX and YX directions, Filters A, B, and D are direction-invariant; Filter C, however, shows different distributions and different mean radii in each direction. This is indicative of preferential alignment of the pore-formers, which were rice hulls, in the direction normal to the applied force while pressing the filter.

Table 4-2: Mean pore radius by filter and direction

	Filter A	Filter B	Filter C	Filter D
Mean r_Z (μm)	12.97	12.52	13.96	14.27
Mean r_Y (μm)	12.85	12.10	7.83	13.05

4.3.4 Tortuosity

The tortuosity factor calculated for each section per filter indicated that Filter B was uniform throughout the thickness of the wall, while Filter C had uniform porosity (volume fraction) but had varying tortuosity over the same distance (Table 4-3). Filter A and Filter D both had varying tortuosity factors and porosities over the through-thickness of the filter wall (Figure 4-27).

Filter C had the highest tortuosity factors ranging from 13 to 39 (corresponding to tortuosity ranging 3.6-6.2). The through-thickness porosity profile was relatively uniform, however the distribution focused primarily within the smaller pores of <15 μm. From volume-rendered data it was observed that Filter C had elongated pores compressed in through-thickness directions resulting in preferentially aligned pores in the direction perpendicular to the flow. (Figure 4-19). This void geometry will result in longer residence time of water in the filter as there seem to be no obvious micro-scale pathways present due to poor inter-void connectivity; this is confirmed by large tortuosity values. It is suspected that a network of nano- or meso-pores connects the micro-scale pores as the filter functionally operates, however these are not detected by micro X-ray CT.

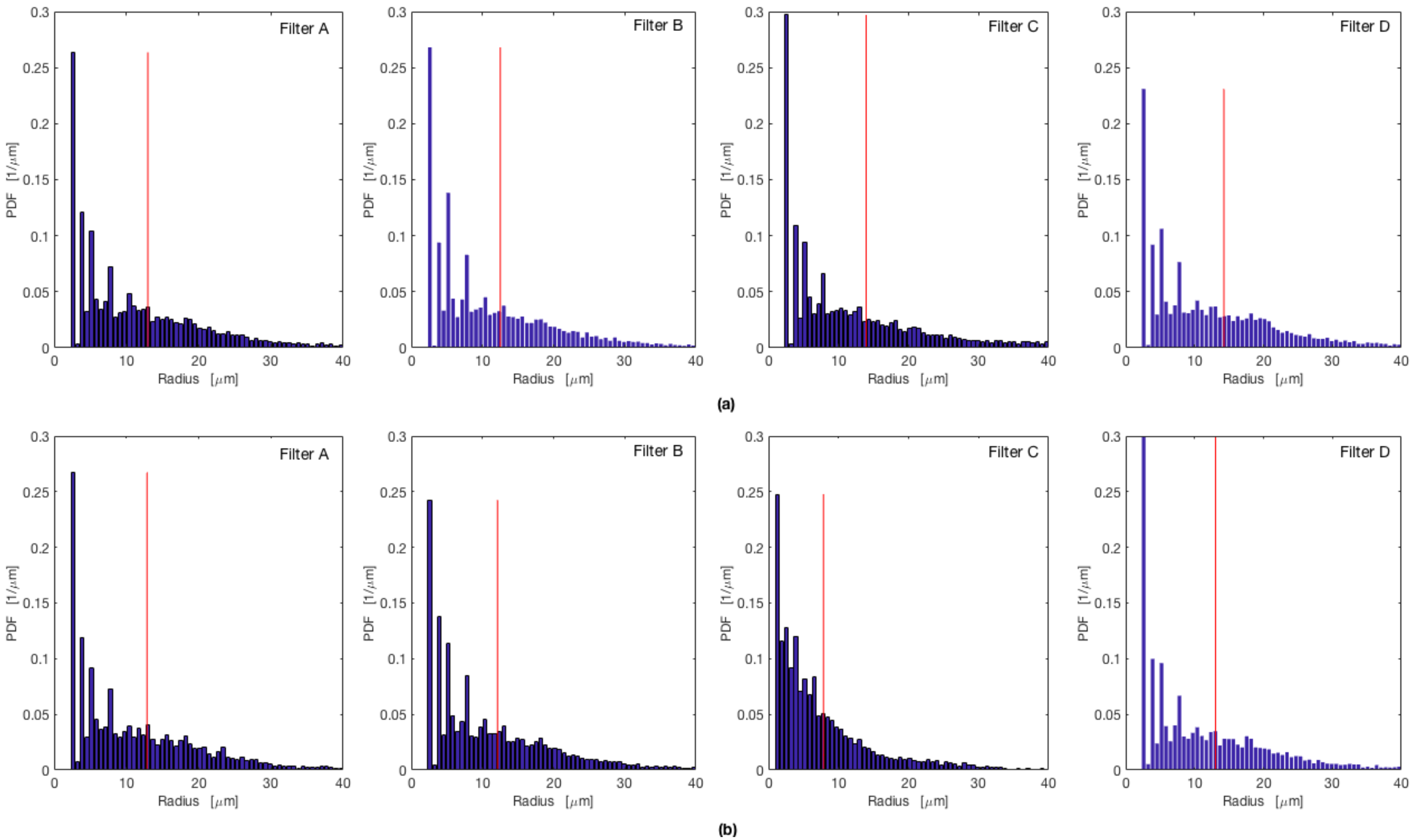


Figure 4-26: Pore size distributions of each filter with mean radius denoted by red line: (a) ZX Direction; (b) YX Direction

Filter D had an infinite tortuosity factor, meaning that flow did not continue across that section. Similar to Filter C, it is suspected that a network of nano- or meso-pores connects the micro-scale pores as the filter is functional. A second possibility is that the chosen sample was not representative of the entire filter as it contained a solid region larger than the sample.

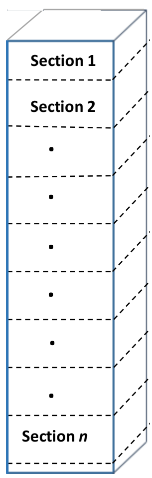


Table 4-3: Tortuosity factor and volume fraction for sections of filter

	Filter A		Filter B		Filter C		Filter D	
Section Thickness, delta z (μm)	682.50		1040		780		1365	
	Tau Factor	Volume Fraction	Tau Factor	Volume Fraction	Tau Factor	Volume Fraction	Tau Factor	Volume Fraction
Section 1	1.97	0.53	4.83	0.42	15.19	0.28	29.99	0.33
Section 2	--	--	5.24	0.44	19.57	0.25	Inf	0.32
Section 3	7.90	0.21	5.18	0.43	14.29	0.24	--	--
Section 4	9.10	0.25	3.86	0.45	38.95	0.24	--	--
Section 5	3.33	0.47	--	--	21.19	0.25	--	--
Section 6	5.46	0.45	--	--	13.75	0.26	--	--
Section 7	11.65	0.43	--	--	--	--	--	--

4.3.5 Formation Factor

Formation factor was plotted against the porosity for each sample (Figure 4-28). The formation factor for Filter A decreased as the porosity of the sample increased. The formation factors for Filter B were relatively consistent (4.4-5.2) across a small range of porosities (0.42-0.45). Although Filters A, B, and D are all made from sawdust, the formation factor clearly shows that the sawdust size and distribution varied between the different manufacturers.

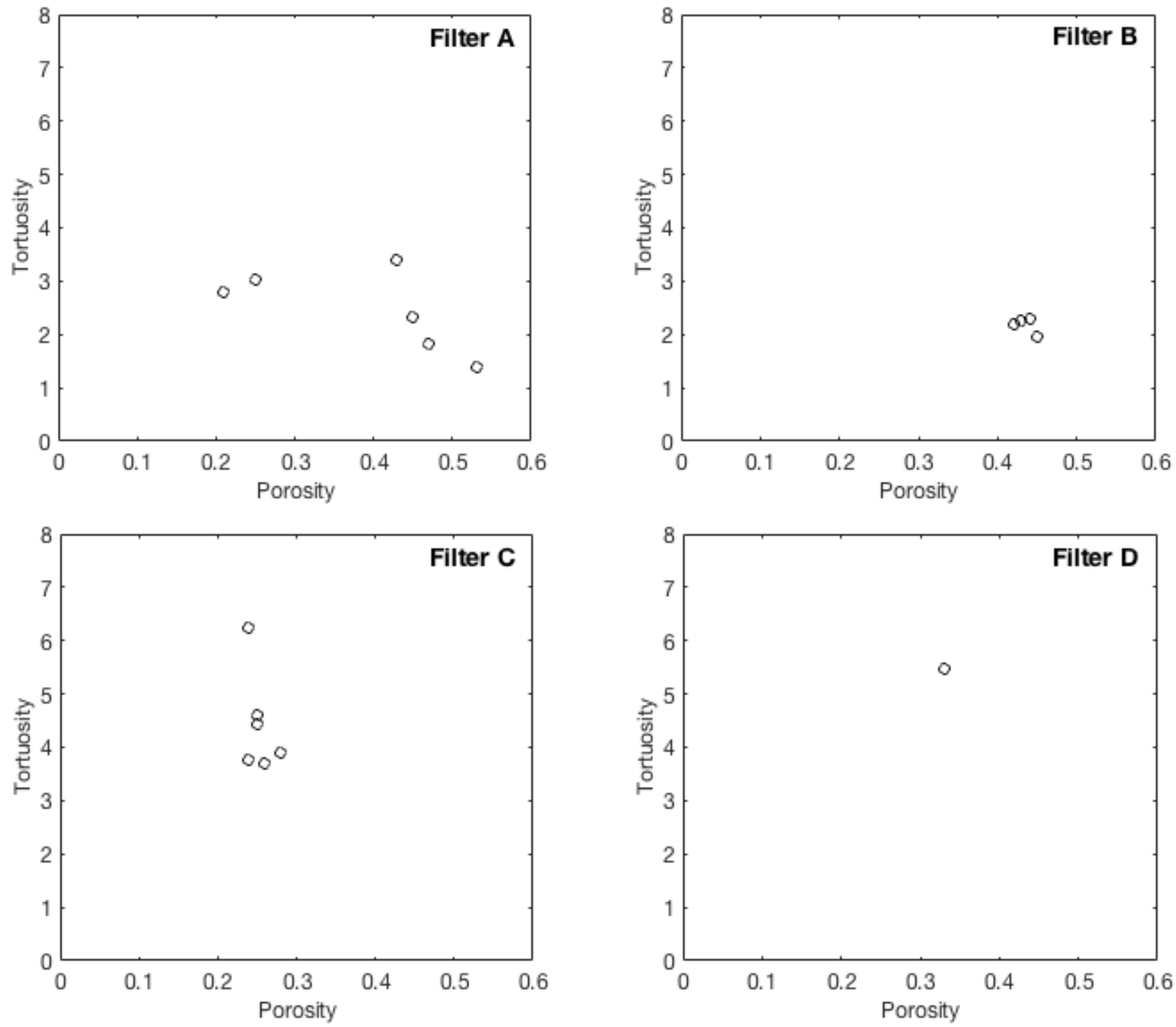


Figure 4-27: Tortuosity and porosity: (a) Filter A; (b) Filter B; (c) Filter C; (d) Filter D

For Filter C the formation factors ranged from 14.3-26.0 over a small porosity range (0.24-0.28). This gives an indication that the pores in Filter C are preferentially aligned in one direction as already indicated by the mean pore radius, pore size distribution, and tortuosity.

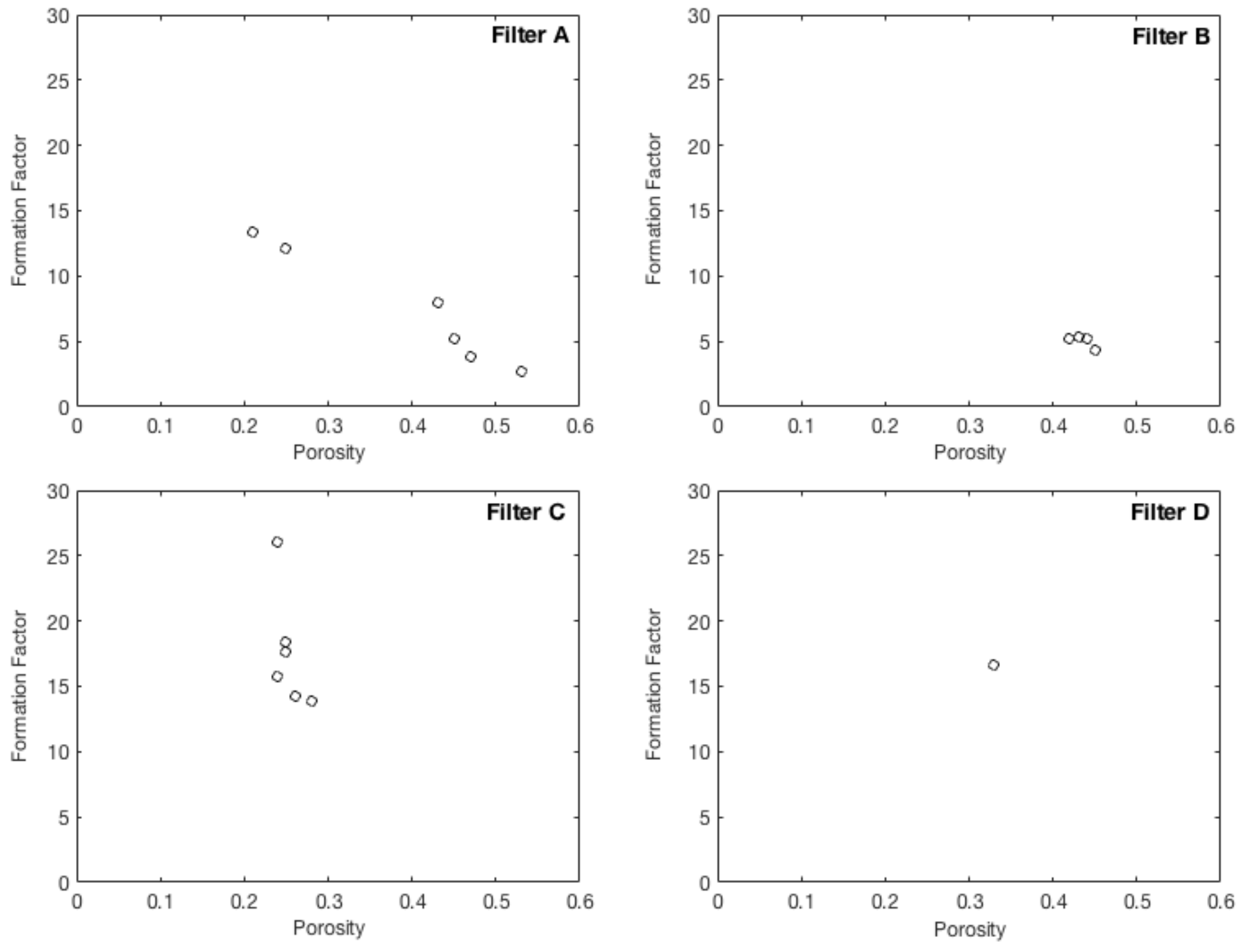


Figure 4-28: Formation factors by porosity: (a) Filter A; (b) Filter B; (c) Filter C; (d) Filter D

4.3.6 Ellipsoid shapes

Ellipsoids did not show any tendency towards being more prolate or oblate when axis ratios were plotted, and there was a tendency for there to be more more data cluster along the line marking a spherical pore (Figure 4-29). The only observation that can be made from these plots is that Filter B has a higher density of ellipsoids that fit to pores than other filters. Filter B did not have the largest porosity or significantly more pores identified in the PSD; therefore, it is concluded that the pores of Filter B must have been more ellipsoidal in nature, as pores that had an extremely small or large axis in comparison to the others results in an unplottable NaN.

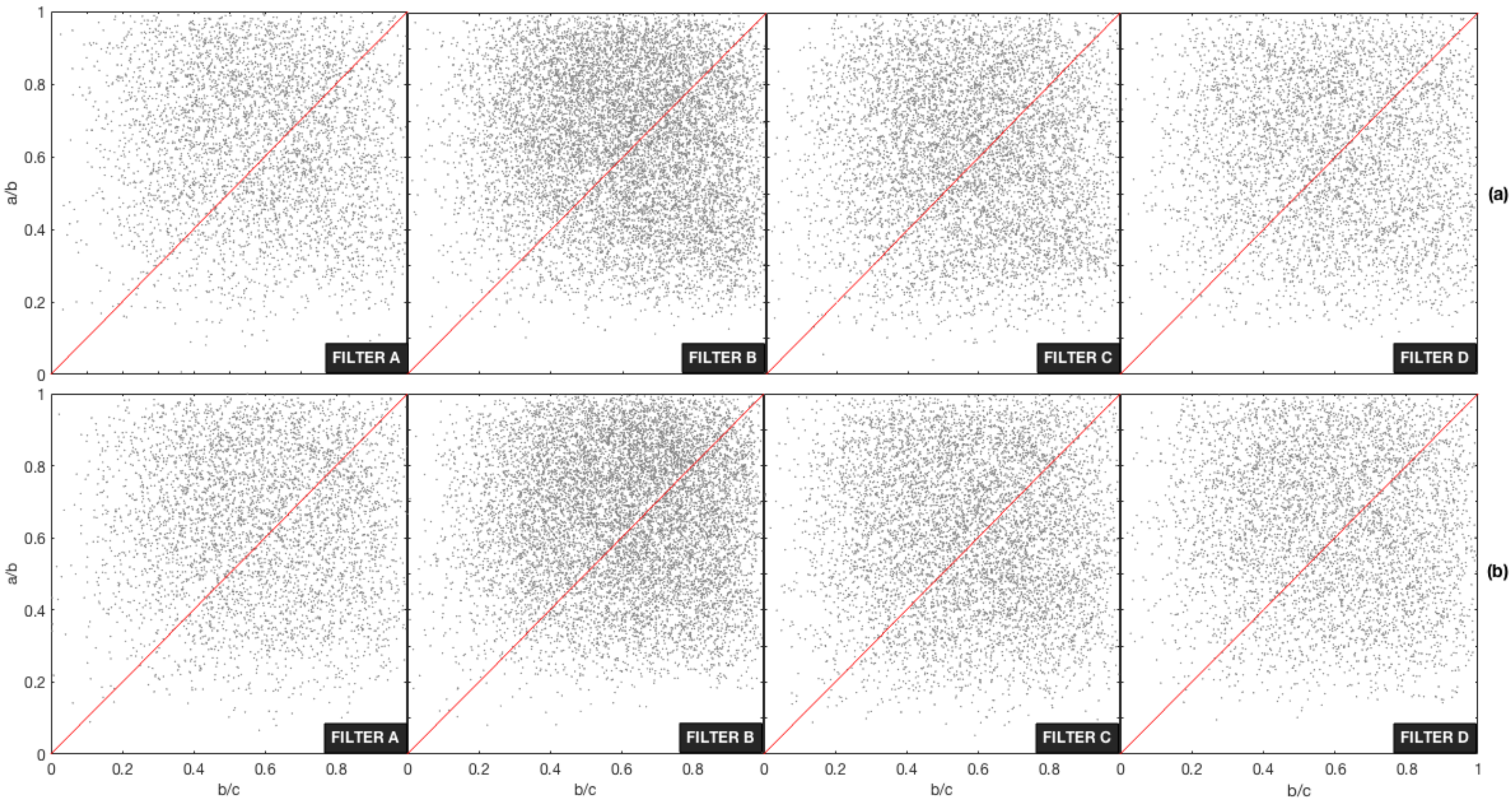


Figure 4-29: Ellipses plotted as ratios of their axes with a line marking spherical pores: (a) ZX Direction; (b) YX Direction

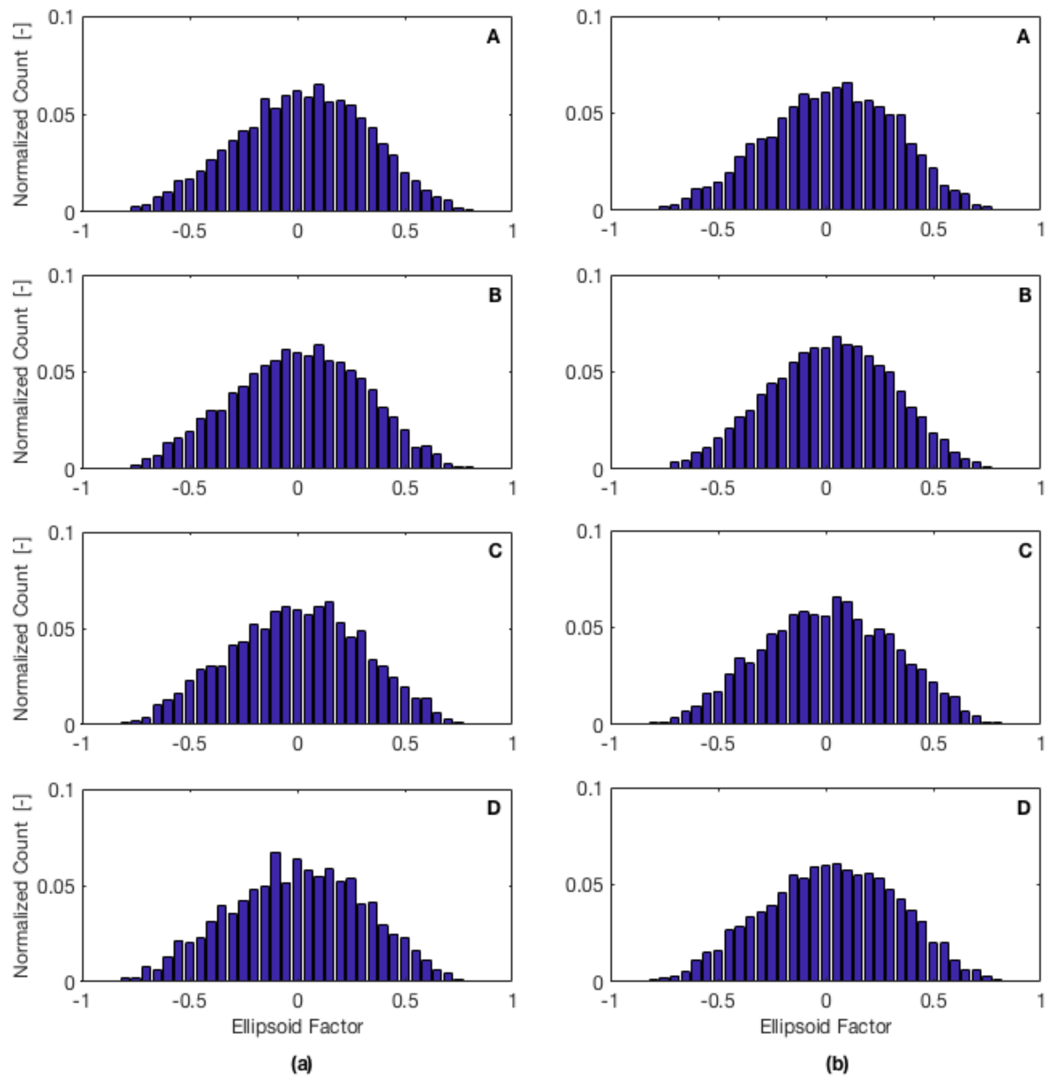


Figure 4-30: Distribution of ellipsoid factors for Filters A-D, where -1 is oblate, 0 is spherical, 1 is prolate: (a) ZX Direction; (b) YX Direction.

From the normalized histograms of EF for each filter, it can be seen that there is not much tendency towards either oblate or prolate pores, and the peak occurs mostly around a spherical EF = 0 value (Figure 4-30). All YX histograms have ellipsoids that are slightly prolate, while this only occurs in the ZX direction for Filter A. None of the filters had oblate, or discus, preference for EF. In comparing all four samples at once, the slight YX prolate tendency is even more pronounced (Figure 4-32), while ZX direction pores remain clustered around 0 (Figure 4-31).

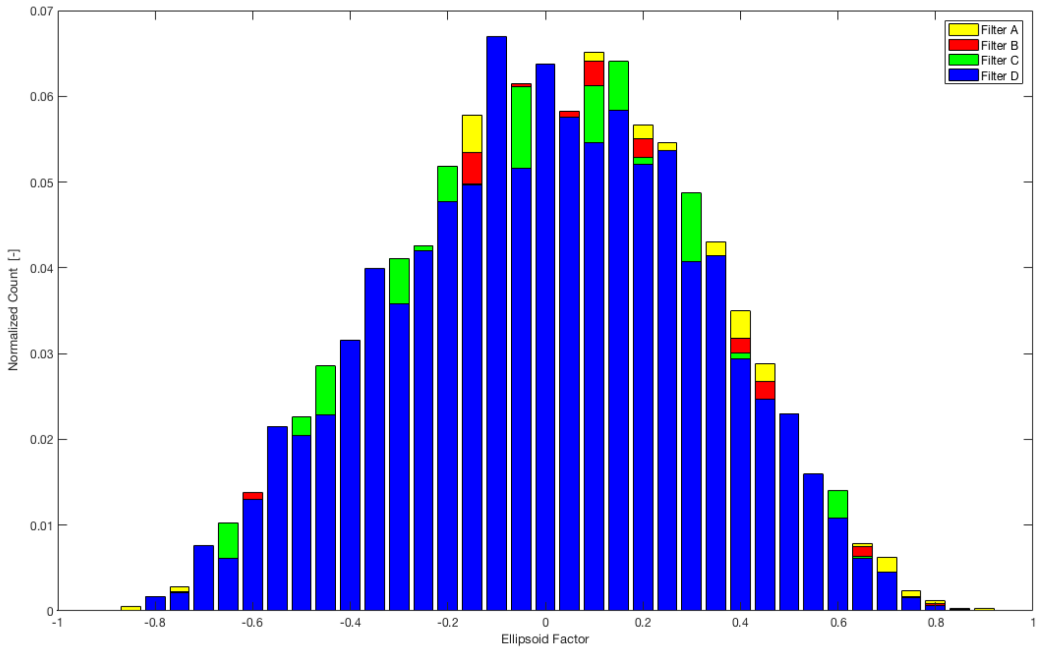


Figure 4-31: Comparison of Ellipsoid Factor histogram Filters A-D in ZX Direction

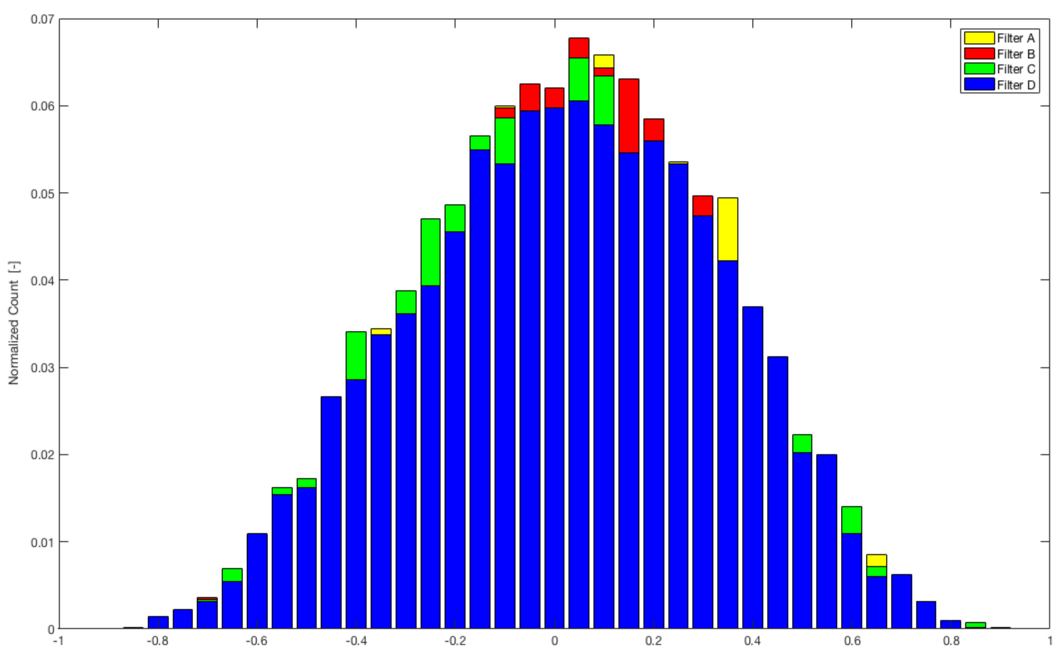


Figure 4-32:Comparison of Ellipsoid Factor histogram Filters A-D in YX Direction

Intuitively, these results are surprising because the volume rendered images hint at finding a preferential ellipsoid factor in Filter C with all of the rice hull pores aligned normal to the direction of force.

A possible explanation for why the EF routine is not generating more shape preferential results is because of the way the routine was run on the small subdivided image stack. This would automatically limit the size of the largest ellipsoid axis by the thickness of the subdivided stack.

The ellipsoids generated during the Ellipsoid Factor routine were further used to calculate the anisotropy of each sample. The degree of anisotropy of the the filters in each direction ranging from 0 (isotropic) to 1 (anisotropic) yielded that Filter C had the highest degree of anisotropy and Filter B had the lowest (Table 4-4).

Table 4-4: Degree of anisotropy of each filter in ZX and YX directions

	ZX	YX
Filter A	0.517	0.512
Filter B	0.375	0.397
Filter C	0.572	0.534
Filter D	0.500	0.515

Additionally, the fabric tensors for each of the filters were calculated and the eigenvectors and eigenvalues calculated based on the mean intercept length method (Table 4-5 - Table 4-6).

Table 4-5: Fabric tensor of eigenvectors for filters in ZX and YX directions

Filter	$V_{1,1}$	$V_{1,2}$	$V_{1,3}$	$V_{2,1}$	$V_{2,2}$	$V_{2,3}$	$V_{3,1}$	$V_{3,2}$	$V_{3,3}$
A-ZX	0.95	0.10	0.30	-0.30	-0.09	0.95	0.12	-0.99	-0.05
A-YX	-0.95	-0.10	0.31	-0.13	0.99	-0.07	0.30	0.11	0.95
B-ZX	0.98	-0.19	0.03	-0.19	-0.98	0.03	-0.02	0.03	1.00
B-YX	0.96	-0.27	-0.05	-0.05	0.01	-1.00	-0.27	-0.96	0.00
C-ZX	-0.98	0.15	-0.09	-0.15	-0.44	0.89	0.10	0.89	0.46
C-YX	-0.65	0.73	-0.22	0.67	0.69	0.28	-0.35	-0.03	0.94
D-ZX	-0.99	-0.10	-0.10	0.14	-0.64	-0.76	0.01	-0.76	0.65
D-YX	-0.99	-0.10	0.10	0.05	-0.90	-0.42	0.13	-0.42	0.90

The eigenvalues for Filter B were were the largest in each principal direction while those in Filter A were the smallest.

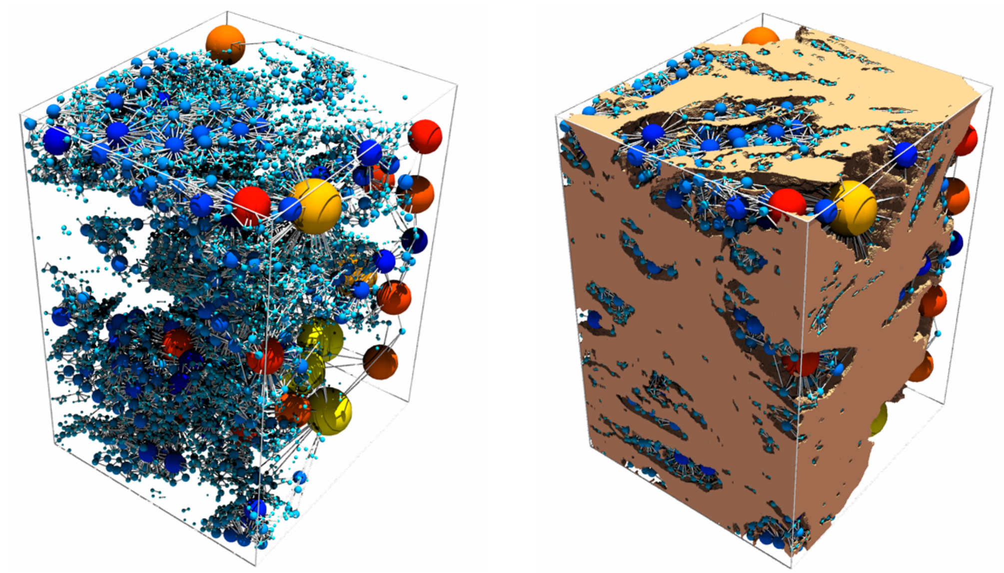
Table 4-6: Fabric tensor eigenvalues for filters in ZX and YX directions

Filter	D1	D2	D3
A-ZX	1.23	1.85	2.54
A-YX	1.37	2.08	2.81
B-ZX	5.70	7.04	9.12
B-YX	5.50	7.30	9.12
C-ZX	2.42	3.54	5.65
C-YX	2.73	3.05	5.86
D-ZX	2.21	3.59	4.42
D-YX	2.31	3.67	4.77

$\times 10^{-4}$

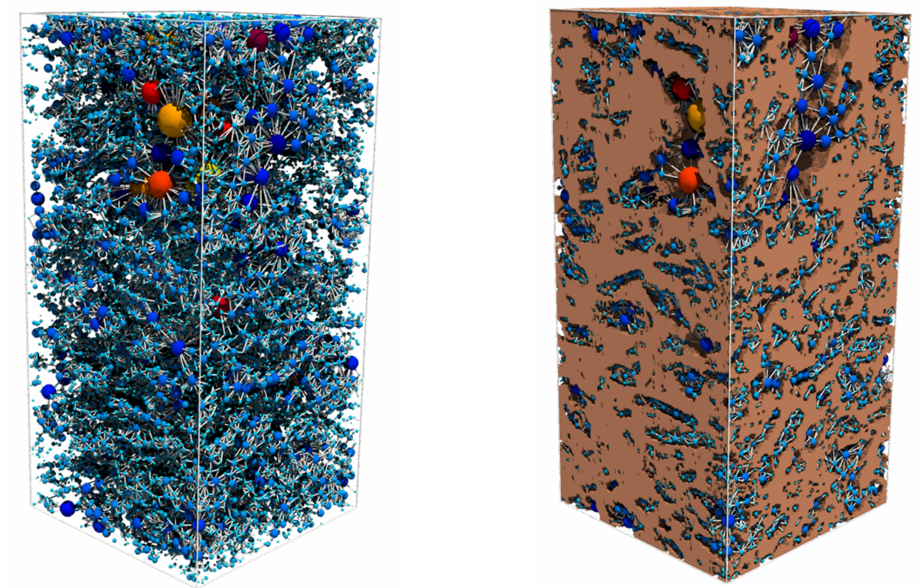
4.3.7 Pore Network Model

Pore Network Extraction Pore network extraction is the process of representing void space from a micro-CT image as a simplified networks of pores and throats using spheres and tubes (Figure 4-33 - Figure 4-36).



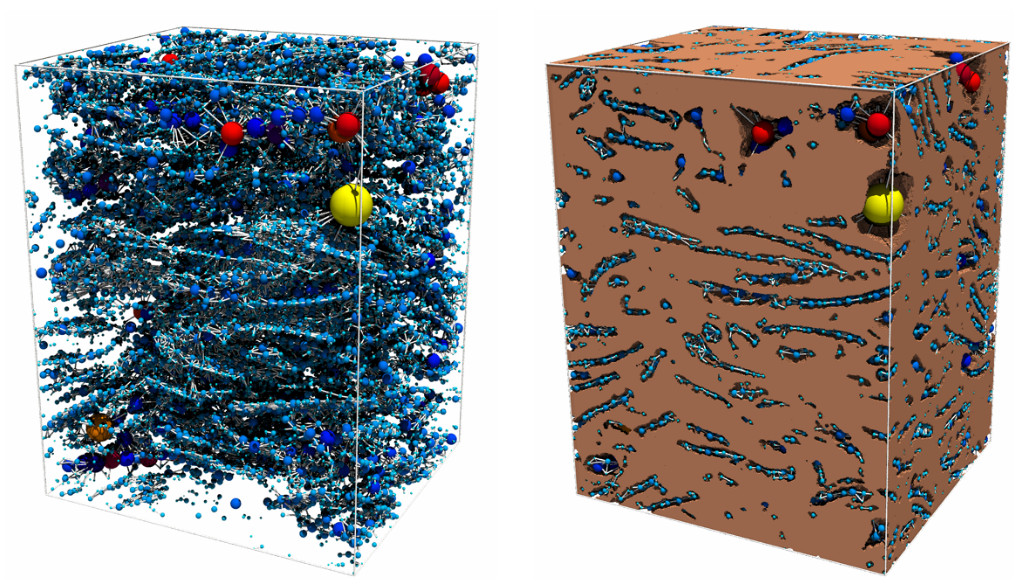
(a) **(b)**

Figure 4-33: Pore network extraction of Filter A: (a) Pore network where spheres are pores and tubes are throats; (b) Solid image overlaid on the pore network for visualization



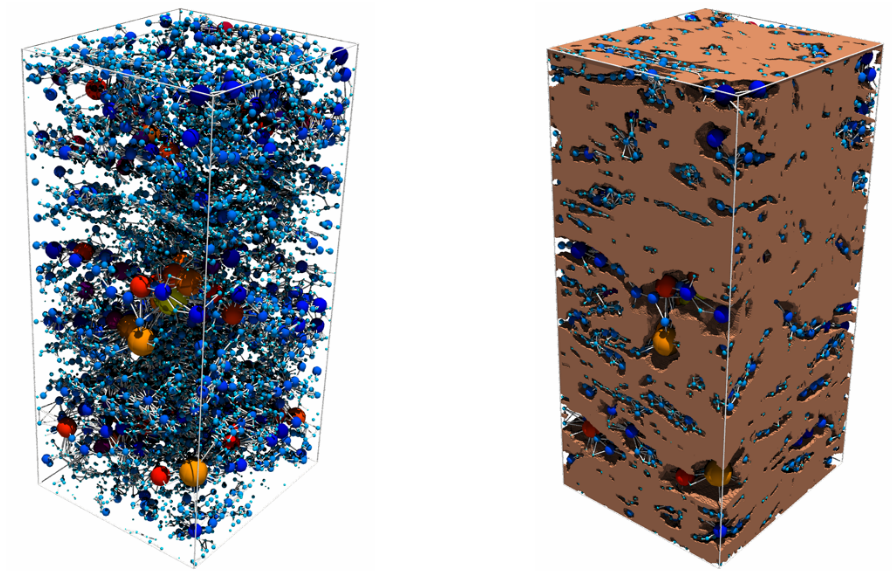
(a) **(b)**

Figure 4-34: Pore network extraction of Filter B: (a) Pore network where spheres are pores and tubes are throats; (b) Solid image overlaid on the pore network for visualization



(a) **(b)**

Figure 4-35: Pore network extraction of Filter C: (a) Pore network where spheres are pores and tubes are throats; (b) Solid image overlaid on the pore network for visualization



(a) **(b)**

Figure 4-36: Pore network extraction of Filter D: (a) Pore network where spheres are pores and tubes are throats; (b) Solid image overlaid on the pore network for visualization

A proprietary and novel algorithm was used to extract the pore networks in this study. The advantage of the network is that it can be used as a representative network for predictive modeling of filter behavior. Pore network parameters are calculated for pore and throat size distributions as well as throat length and coordination number (Figure 4-37 - Figure 4-39).

Pore Network Model The extraction of the pore network is used to calculate several morphological parameters of the filters including pore size distributions. These distributions show that there is similarity in pore size as compared to the ImageJ PSD calculations. Filters B and D have significantly more pores than Filter A, and the largest frequency of pore size from the pore network models is around

12.5 μm in radius. From the pore network models, filters A and B have more throats than Filter D; the frequency for all filters was highest at a radius of approximately 12.5 μm. The maximum pore and throat radius for Filter B was the smallest of all of the filters at approximately 50 μm, while the others were approximately 75 μm.

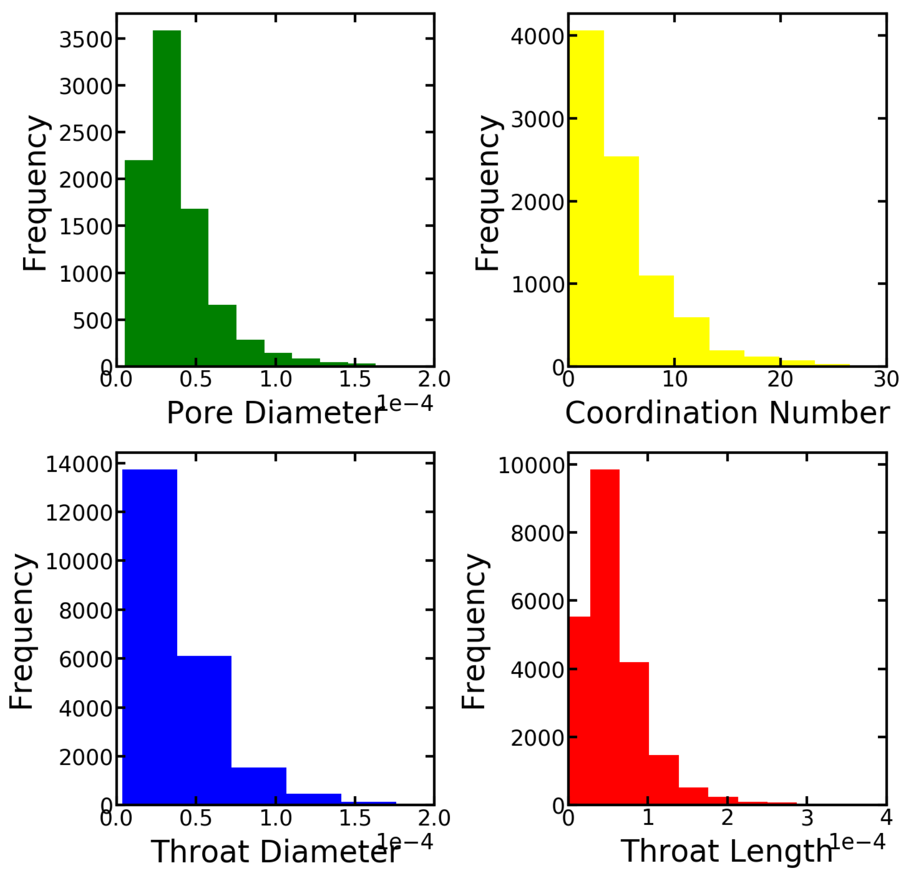


Figure 4-37: Filter A pore and throat sizing histograms

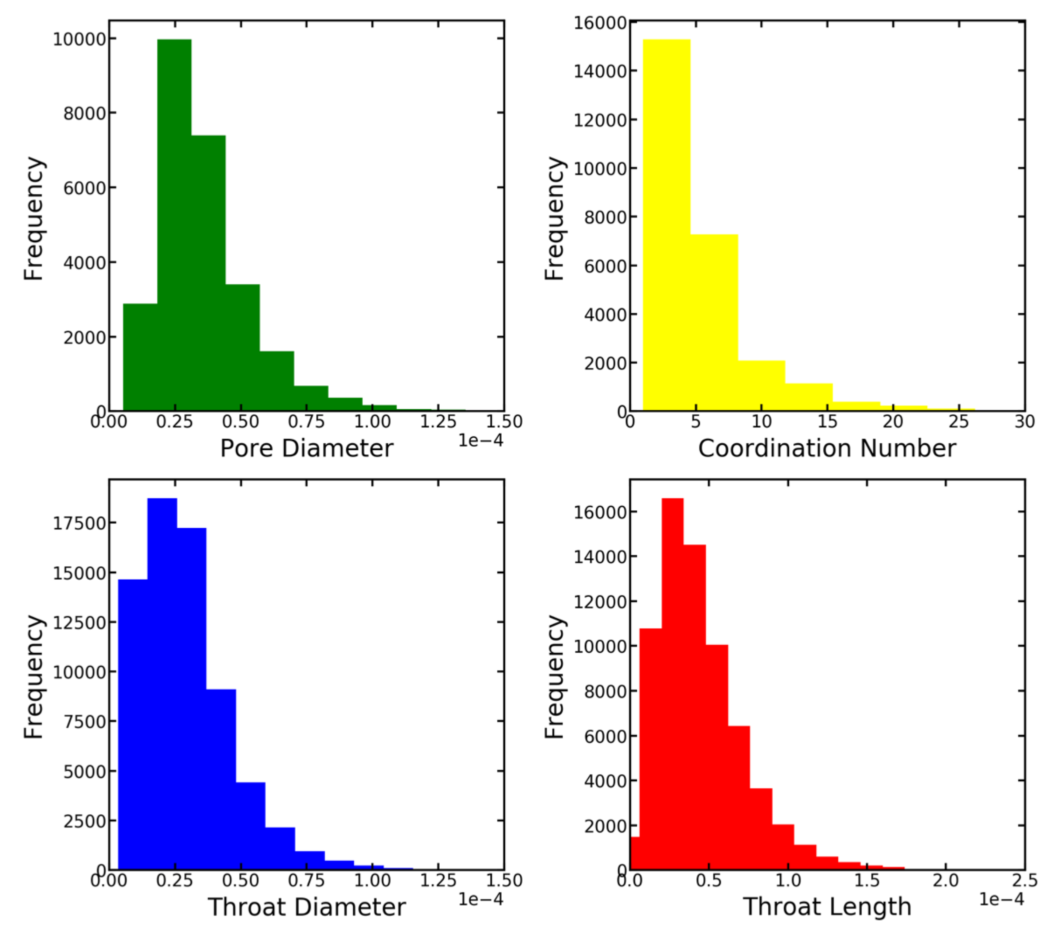


Figure 4-38: Filter B pore and throat sizing histograms

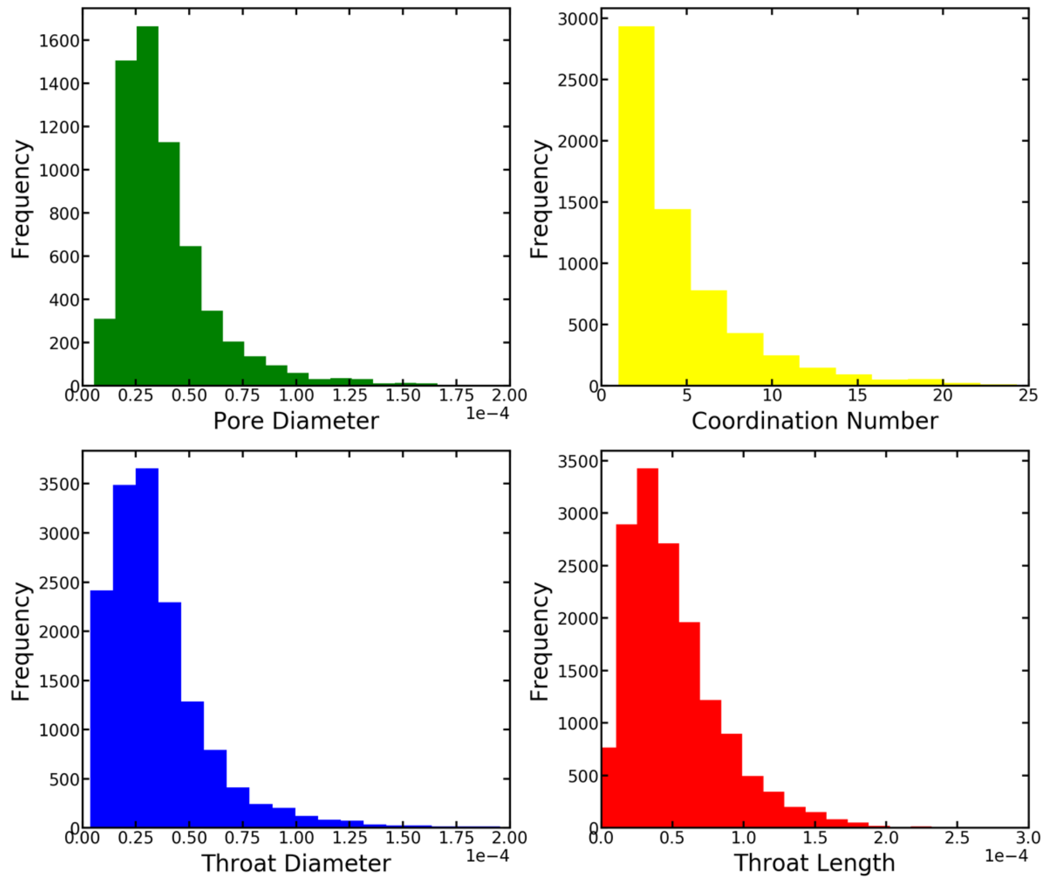


Figure 4-39: Filter D pore and throat sizing histograms

Permeability For the frustum shaped filter (Filter C), the permeability value, *k*, that minimized the Explicit Euler error was 2.3448×10^{-14} m^2 and the value that minimized the Runge-Kutta error was 2.669×10^{-15} m^2. The Explicit Euler model approximated both the head height and the resulting volume of filtrate experimental data better than the Runge-Kutta model (Figure 4-40). The first hour flow rate for the frustum filter was 1.365 L/hr.

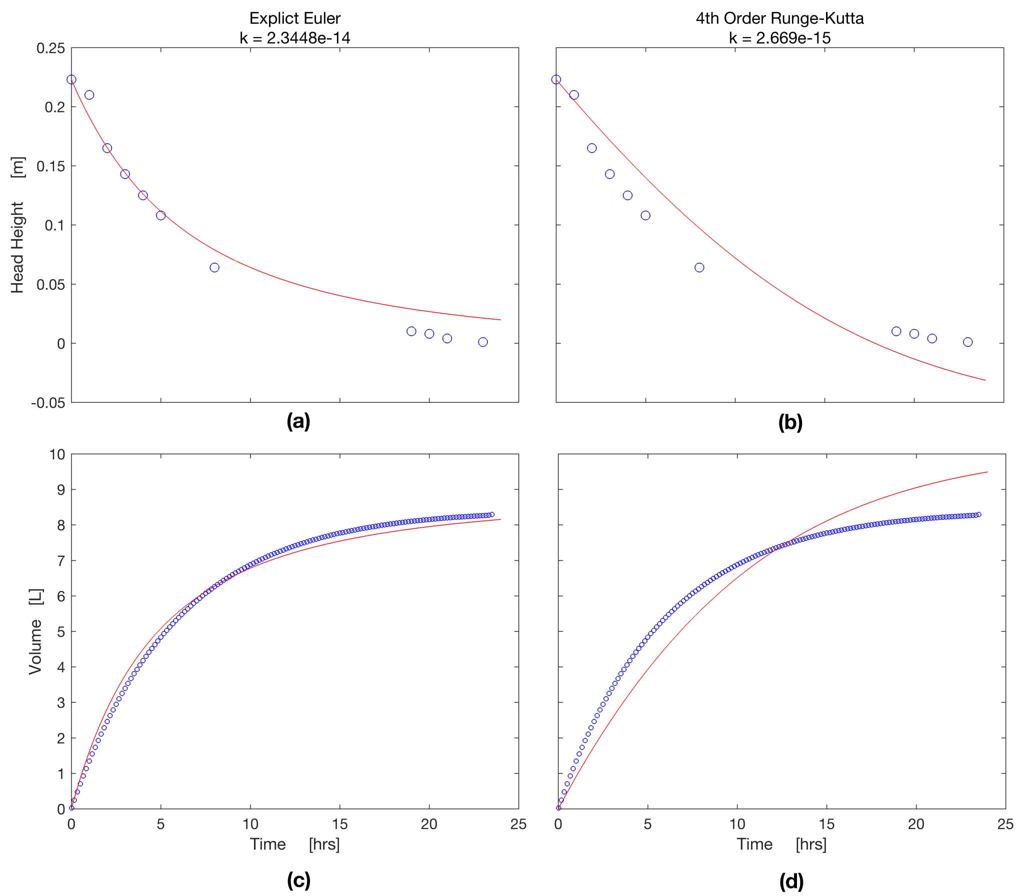


Figure 4-40: Frustum shaped filter head height models for (a) Explict Euler and (b) Runge-Kutta routines. Volume models for (a) Explict Euler and (b) Runge-Kutta routines.

For the paraboloid filter (Filter D) the permeability constant that minimized the error in the head height equation was $k=2.00 \times 10^{-15}$ (Figure 4-41). The first hour flow rate for the paraboloid filter was 1.175 L/hr.

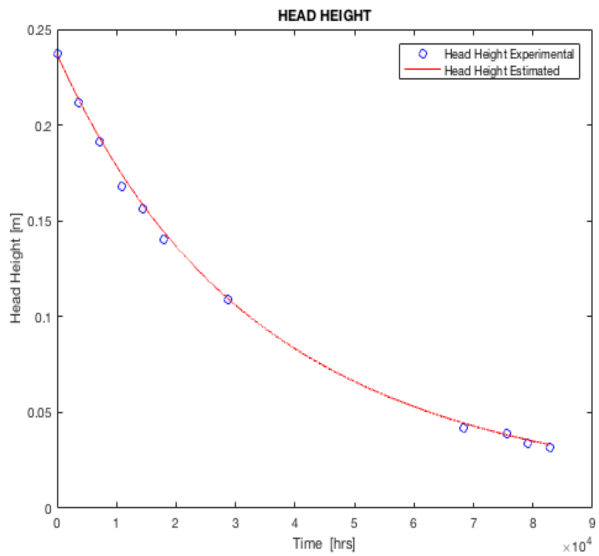


Figure 4-41: Falling head experimental and model data for paraboloid filter

The pore network models were also run in a simulated mercury intrusion porositmetry routine to calculate the permeability of the pore networks. This calculation of permeability yielded the following tensor

Filters	D_1	D_2	D_3
A	1.965132×10^{-13}	3.645462×10^{-12}	2.628468×10^{-15}
B	3.724909×10^{-13}	7.368058×10^{-13}	4.165919×10^{-13}
C	--	--	--
D	2.133684×10^{-12}	1.787683×10^{-12}	7.226589×10^{-14}

4.4 Discussion

Overall, this study has presented a method for and validation of four ceramic pot water filter samples via X-ray micro-CT, image processing, and modeling. Results suggest 1) porosity alone is a limited explanation of pore network morphology; 2) mean pore radius is larger than bacteria, although 50% of pore radii were <15 μm, indicating that pore size alone does not account for effective filtration via size exclusion; 3) tortuosity, ellipsoid factor, and anisotropy are critical parameters in extending the understanding of morphology of the filter; 4) pore network models provide permeability estimates on the same order as the falling head tests and PSDs similar to the ImageJ/Fiji algorithms; and, 5) the developed methods are computationally intensive due to sample size.

Measurement of porosity as a classic descriptor of pore network morphology is common. Other studies on ceramic pot water filters have measured porosities at: 34.7-38.8% (Oyanedel-Craver & Smith 2008), 36-47% (Plappally *et al.* 2009), approximately 36-47% (Yakub *et al.* 2013), 47.9-64.6% (Rayner *et al.* 2017), 49.5% (Matthies *et al.* 2015), ~8-45% (Scannell 2016). With the exception of the low porosity reported by Scannell, porosities in this study were similar, ranging from 25-36%. Significant variation of the porosity (10-60%) across the thickness of the filter in the YX direction for Filter A and Filter D indicate that there may be regions where pore-formers were mixed unevenly. A prime limitation on the use of porosity is that it is difficult to ascertain whether the pores are large or small and how connected they are.

Pore size distribution is a good parameter for classifying the radius of pores. Other studies on ceramic pot filters have reported mean pore radii 1.015 μm – 7.15 μm (Oyanedel-Craver & Smith 2008). This is smaller than the mean pore radii in this study (7.8-14.3 μm) but the filters from all of these studies were from varying factories. The mean pore radii that we found is not small enough to effectively mechanically filter via size exclusion alone. Yakub *et. al.* reported a majority of pore radii fell between 0.025 and 0.05 μm, and also that there was a distribution of radii spanning a range of nano-pore sizes (Yakub *et al.* 2013). In an Indonesian filter, pore radii were reported to be 1 – 40 μm (Matthies *et al.* 2015). The limitation of PSD as a metric is that it does not give an indication of connectivity, e.g. are small pores connected to small pores or large pores. This is important for understanding how retained particles become entrapped in the filter and also can indicated if there may be issues such as preferential cracks that form.

Tortuosity is a good indicator of the connectivity of a pore network. Other ceramic pot filter studies have reported tortuosity factors of 7.8 – 13.2 (van Halem *et al.* 2007) and 10-60 (Yakub *et al.* 2013). Two filters in this study were demonstrative of the effect of pore-formers on tortuosity. Filter B had fairly uniform porosity (0.42-0.45) and uniform tortuosity factors (3.86-5.24) throughout the sections. Filter C had a narrow porosity range (0.24-0.28) but had tortuosity factors that ranged 13.75-38.95. While the porosities indicate that each of these filters had well mixed pore-formers, the tortuosity factor differences suggest that the pore-formers in Filter C were, at times, not aligned with the direction of flow. Further, the higher tortuosities in Filter C suggest that filtrate has a longer residence time in the network, which contradicts van der Laan's postulation that rice husk filters have a shorter residence time meaning that *E. coli* inactivation occurs primarily during silver contact in storage (van der Laan *et al.* 2014). The porosities and tortuosity factors in Filters A and D were not uniform within a sample and even indicated regions were flow could not pass through the filter because of a lack of connected pores.

In general, permeability values from this study were on the same order of magnitude as permeability values found in literature for filters manufactured using different clays and burn-out materials. Our permeability values ranged $2.448\text{x}10^{-14}$-$2.00\text{x}10^{-15}$ m^2, while others reported ranges from $0.1\text{x}10^{-14}$ – $5.0\text{x}10^{-14}$ m^2 (Annan *et al.* 2014; Yakub *et al.* 2013). The hydraulic conductivities of filters in literature were between 1.5 and $4.4\text{x}10^{-7}$ m/s (Matthies *et al.* 2015) and 1.15–$5.01\text{x}10^{-7}$ m/s (Oyanedel-Craver & Smith 2008), which were smaller than those reported by van Halem (1.3–$1.37\text{x}10^{-7}$ m/s) and Annan *et al.* ($1.46\text{x}10^{-7}$ m/s) (Annan *et al.* 2014; van Halem *et al.* 2007).

While this study has yielded fruitful information about tortuosity and presented porosities and PSDs using a different experimental basis than other studies of ceramic pot water filters, it was not without its challenges. The large size of image stacks for these samples were a challenge to deal with from a RAM point of view, as they required significant memory in order to be opened and processed. Routines, such as TauFactor, were run on the Tufts University research computing cluster accessing the maximum allotted memory, processing power, and time and were still unable to calculate values for some sections. Additionally, issues with Fiji/ImageJ routines crashing when processing full image-stacks led to the choice to subdivide them and process them on 22 individual computers with less RAM. When running 24/7, this computer lab was able to process *Ellipsoid Factor* and *Particle Analyzer* routines on the subdivisions of 4 samples in 2 orientations (ZX and YX) in 7 weeks. However, there are possibilities that subdividing the samples so much, effectively forcing representative element volumes (REV), introduced errors such as limiting the growth of ellipsoids. Choosing to calculate on smaller samples, or REVs, for Filters B and C may have been possible given their uniformity, but may not have been a good choice to capture the variance in Filters A and D.

4.5 Conclusions

The application of X-ray micro-CT scans to ceramic pot filter samples provided a novel way to image and study the pore network morphology of these filters. If this methodology were to be utilized again, the following are recommendations:

1) Used repeated samples from the same filter to test for morphological variation within filters and to provide sample size for statistical analysis.

2) Image samples from a precisely manufactured field filter or laboratory manufactured ceramic filter disc to control for manufacturing defects and characterize the properties of a known material via the X-ray micro-CT technique before extending the methodology to filters manufactured under less stringent conditions.

3) Vary the clay:burn-out ratio and image filters across a range of ratios to investigate the impact of ratios on morphology, particularly tortuosity.

4) Image filters pre and post long-term loading to quantify the effects of fouling on network morphology.

5) Conduct a representative element volume (REV) and pore network modelsto quantify the introduced error that results from subdivision.

This study highlights the continued need for understanding the interaction of manufacturing parameters on filter morphology and its relationship to filter efficacy. While porosity and PSD are decent indicators of filter functionality, the addition of tortuosity to understand network connectivity may be key in helping to optimize performance and production of the filters in the field.

4.6 Acknowledgements

The completion of this work was made possible with assistance from the following people: Iryna Zenyuk and Andrew Shum (beamline image collection); Liam Connelly, Andrew Shum, and Stanley Normile (Fiji/ImageJ teachings and algorithms); Zachary Chen (reconstructions and assistance running the 22 computer lab); Sam Cooper (updating TauFactor to handle colossal datasets); Jeff Gostick (network extraction, OpenPNM algorithm development, and answering a myriad of minutiae questions); Justine Rayner (filter samples, advice, and data on ceramic pot filters); Douglas Matson (supporting initials iterations of this study at NASA and transporting filters from his travels). Mesiaki Kimirei from Safe Water Ceramics East Africa for filters and assistance and Chujio Ceramics in Kenya for filters. Most importantly, this study was made possible under the vision and direction of Iryna Zenyuk who shared her laboratory and computing resources and her knowledge of image processing micro-CT scans and pore network morphology.

5 Conclusions

5.1 Research Summary

This dissertation investigated technologies associated with safe water provision at two scales: community and household. First, literature on Water Safety Plans was gathered and analyzed to understand what evidence and lessons on WSP implementations exist, and where gaps remain to better inform key stakeholders of research needs in this area. Second, a multi-country evaluation of rural, community-managed WSP implementations was conducted using a mixed methods protocol to understand how the WSP process was translated into these contexts and to evaluate the functionality of these implementations. Third, an advanced imaging technique was used on household ceramic water filters to characterize the pore network morphology of engineered pathways and to develop a model to mimic filtration of natural waters in these filters. Specific summaries of contributions from each study are as follows:

Chapter 2 The goal of this review was to collate lessons learned and evaluation results by general contexts, rural implementations, and focus country case studies. Of the 53 documents in the study, 12 were included for general WSP lessons learned; 12 were pertinent to the rural implementation context; 11 pertained to WSPs in case study countries; and 24 contained information related to evaluation of outcomes and impacts. Overall, three themes in the lessons learned were identified in this paper: 1) need for support to WSP implementers; 2) need for evaluation of outcomes and impacts; and, 3) need for adaptation of WSP processes to the implementation context. In general, outcome and impact evaluation data demonstrating WSP value across the outcomes of the WSP evaluation framework were weak.

Chapter 3 In an evaluation of rural, community-managed WSP implementations in four countries we found, overall: 1) incomplete WSP implementations; 2) no documented microbiological water quality improvements from WSPs; and, 3) small water supply operations improvements. Our research on the effectiveness of extending WSPs from large, urban systems to community-managed supplies identified three core challenges: 1) villages with multiple (private) drinking water sources may not have full WSP coverage, thereby limiting the potential for WSP benefits and questioning the appropriateness of WSP implementations in these settings; 2) to ensure WSP processes are not diluted, thorough training of trainers and training of villages on the complete six-task WSP implementation is critical; and, 3) resource support is required for design, hardware, and technical services to improve drinking water quality.

Chapter 4 Overall, this study presented a method for, and validation of, four ceramic pot water filter samples via X-ray micro-CT, image processing, and modeling. Results suggest 1) porosity alone is a limited explanation of pore network morphology; 2) mean pore radius is larger than bacteria, although 50% of pore radii were <15 μm, indicating that pore size alone does not account for effective filtration via size exclusion, particularly when the scans were limited to a resolution of 1.3 μm; 3) tortuosity, ellipsoid factor, and anisotropy are critical parameters in extending the understanding of morphology of the filter; 4) pore network models provide permeability estimates on the same order as the falling head tests and PSDs similar to the ImageJ/Fiji algorithms; and, 5) the developed methods are computationally intensive due to sample size.

5.2 Recommendations and future work

5.2.1 Water Safety Plans

The WSP results from the four country study raise important questions about how to present the data to implementers of these WSP programs. It can be difficult, when presented with results that are not positive to determine the most appropriate method of dissemination. As WSPs will be the primary form of advocated and supported water management strategy, it is useful to be getting any information on performance at this early stage in programs to identify potential roadblocks in effective programming as implementations scale-up. Results from this study should be used to motivate reviews of WSP program implementations in each country, focusing on gaps identified in water safety, water security, technical capacity for risk assessment, and capital assistance needs to support short-term improvements and large-scale infrastructure upgrades.

There are significant risks in recommending WSPs for community-managed supplies in the absence of sector support. Partial WSP implementations, a lack of community training, a lack of implementer follow-up, a lack of local enabling environments, and a lack of capital and resource support to improve supply systems and monitoring hinders the potential benefits from implementing a WSP. Additionally, WSP implementation without properly addressing water quality and treatment needs can create a false sense of security that villages are safely managing their water supplies. Implementers need to carefully consider whether the frameworks are in place for WSPs to be implemented. There are many elements of a WSP that are being used in water supply management globally; it is incorrect for implementers to assume that if they are using some elements of the process that they are implementing WSPs as this over represents the outcomes and impacts that would be seeing from the implementations. Until global guidance or a country policy recommends otherwise, a WSP must contain all tasks of the implementation.

Community-managed WSP processes need further development. The mixed evidence found herein on WSP implementations in community-managed, rural water supplies highlights the need for usable WSP processes that are effective in the community. Developing WSP guidance for mixed, multiple, or private water sources, planning in-depth trainings of implementers and communities, and providing resources to the communities are critical.

5.2.2 Morphology of ceramic water filters

Advanced imaging techniques of filters should consider characterizing laboratory manufactured ceramic filters. Ad-hoc manufacturing and microbiological testing data from the filter samples imaged herein highlight the missed opportunities in building a complete dataset to compare tomographic and modeled data against. Utilizing ceramic samples manufactured in a controlled manner allows for more accurate and methodic sample building and a comparison of the ore network to the raw materials.

As the resolution of the micro-CT scans is 1.3 μm, this imaging method does not capture nanopores, which means that this method does not capture pores in the size range of most of the bacteria that may be in the water. Instead, this method is good for imaging the micro- and macropores that result directly from the burn-out material. To image and model pores in the range of interest for bacterial size exclusion would require the use of a nano-CT.

While valuable information on pore networks is gained from this method, it is not recommended that factories attempt to use this characterization technique on their filters. Not only is it financially expensive, it also requires access to specific facilities and researchers with a specialization in this field. However, for researchers in the ceramic pot filter space who are attempting to develop best methods through an understanding of the manufacturing processes, this technique may provide valuable information depending on research goals.

5.3 Closing

Integration of WSPs and HWT is mutually beneficial. In some settings the implementation of a WSP may be the most effective way to ensure safe drinking water, while in others point-of-use water treatment technologies may be the only feasible option. However, these two broad interventions for safe water supply should be viewed as complementary and not competitive; a strategy integrating both intervention methods would address safe water supply concerns across a wider spectrum.

Technologies for the provision of safe water will continue to be developed and implemented as the needs and capabilities of communities' change. It is important to ensure that all parties, from agenda-setters to implementers to academic researchers, pursue evidence based solutions to water supply management and address knowledge gaps to provide communities with achievable and effective interventions. Advancing the technical research around household water treatment technologies is critical to the manufacture of quality products and in supporting standards for certification. With the Sustainable Development Goal mandate for safely managed water supplies, both community and household practices around water and risk management will remain central to the work of governments and implementing partners.

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Annex A – Household Surveys

Number: ____

Household Knowledge, Attitudes, and Practices Survey

A	Enumerator Name		
B	Date and Time of Interview	Date:	Time:
C	Province		
D	Island		
E	Name of the Village		
F	GPS Coordinates	N:	W:

Q1. **(Circle respondent's sex)**

Male	1	Female	0

Q2. How old are you? ____ yrs

Q3. Did you go to school?

Yes	1	No *[Go to Q5]*	0

Q4. What is the highest grade you completed? ____ grade

Q5. How many people live in the household? ____

Q6. I would like to know the age and gender of each person who lives in this house. Let's start with the oldest person in the house.

Who comes next?

I will now ask you some questions about diarrhea. Diarrhea is defined as loose or watery stool (bloody or not) three or more times in 24 hrs.

Of all the household members you just listed, which of them have had diarrhea in the last one week?

Anyone else?

#	Gender *[Circle one]*	Age	Diarrhea *[Circle one]*		
1	M / F		Yes	No	Don't know
2	M / F		Yes	No	Don't know
3	M / F		Yes	No	Don't know
4	M / F		Yes	No	Don't know
5	M / F		Yes	No	Don't know
6	M / F		Yes	No	Don't know
7	M / F		Yes	No	Don't know
8	M / F		Yes	No	Don't know
9	M / F		Yes	No	Don't know
10	M / F		Yes	No	Don't know

Q7. What ways do you know to prevent diarrhea / cholera?

Drink safe water	1	Wash hands	2	Use latrine	3
Cook food	4	Peel vegs / fruit	5	Cover food	6
Clean house	7	Clean dishes	8	Don't know	9
Other:					99

Q8. Do you think you can get sick from water?

Yes	1	No *[Go to Q10]*	0
I don't know *[Go to Q10]*			88

Q9. What kind of sickness can you get from drinking water?

Any more?

Diarrhea	1	Vomiting	2	Stomach ache	3
Fever	4	Cholera	5	Dehydration	6
Don't know	88	Other:			99

Q10. How do you know if your water is safe to drink?

Water is clear	1	No bacteria	2	I treat it	3
Bottled	4	Boiled	5	Chlorinated	6
Filtered	7	Source is clean	8	Storage is clean	9
Don't know	88	Other:			99

Q11. How do you know if your water is not safe to drink?

Water looks dirty	1	Has bacteria	2	From a bad source	3
Makes you sick	4	When not treated	5	Storage is dirty	6
Don't know	88	Other:			99

Q12. Do you believe the water you have in your house today is safe to drink?

Yes	1	No	0	I don't know	88

Q13. What type of toilet do you have? Is it shared?

Latrine on plot	1	Latrine off plot/shared	2	Latrine absent *[Go to Q17]*	3	Refuse *[Go to Q17]*	88

Q14. **(OBSERVE: Does the latrine appear to be in use?)**

Yes	1	No	0	Can't tell	88

Q15. Was the latrine installed as a result of the DWSSP program?

Yes	1	No	0	I don't know	88

Q16. How much did you pay for the latrine?

	VUV	No cost	0	I don't know	88

Q17. What materials do you use to wash your hands?

Yes, dedicated place	1	No dedicated place	0	Refuse	88

Q18. Was a handwashing station installed as a result of the DWSSP program?

Yes	1	No	0	I don't know	88

Q19. Can you show me what you wash your hands with?

Soap	1	Chlorinated water	2	Ash	3
Nothing	4	Ran out	88	Other:	99

Q20. When do you wash your hands?

After using toilet	1	Before collecting water	2	Before eating	3
Before cooking	4	After disposing waste	88	Other:	99

Q21. Where does your household primarily get drinking water from?

Closed well	1	Open well	2	Canal	3
Protected spring	4	Unprotected spring	5	Surface water	6
Rainwater	7	Bottled/bagged	8	Tanker truck	9
Tap at house	10	Tap not at house	11	Other:	99

Q22. Is this from the DWSSP water system?

Yes	1	No	0	I don't know	88

Q23. Do you pay for water?

Yes	1	No *[Go to Q25]*	0	I don't know *[Go to Q25]*	88

Q24. How much do you pay for water?

	VUV	*Per* month/L	No cost	0	I don't know	88

Q25. How many times a day does someone from your household usually collect water? ______ times

Q26. How long does it take to go to your water source, collect water, and come back, each time? ______ min

Q27. Do you collect water from another place?

Yes	1	No *[Go to Q29]*	0	I don't know *[Go to Q29]*	88

Q28. Where else do you get your drinking water from?

Closed well	1	Open well	2	Canal	3
Protected spring	4	Unprotected spring	5	Surface water	6
Rainwater	7	Bottled/bagged	8	Tanker truck	9
Tap at house	10	Tap not at house	11	Other:	99

Q29. Do you currently have any stored drinking water?

Yes *[Go to Q31]*	1	No / Refuse *[Go to Q31]*	0	Don't have	3

Q30. Why don't you currently have any stored drinking water?

Have on-demand system	1	Ran out of all water	2
Ran out of drinking water	3	Other:	99

Q31. May I see your primary drinking water storage container? Even if you do not have water right now, I would like to see the container.

Yes	1	No/Refuse *[Go to Q39]*	0

Q32. OBSERVE: What type of storage container is it?

Bucket	1	Jerry can	2	Other:	99

Q33. OBSERVE: Approximately how many liters is the container?

liters

Q34. OBSERVE: Is the storage container covered?

Yes	1	No	0

Q35. OBSERVE: Is there a tap for dispensing water?

Yes	1	No	0

Q36. OBSERVE: Is there water in the container?

Yes	1	No *[Go to Q39]*	0

Q37. What source did this water come from?

Closed well	1	Open well	2	Canal	3
Protected spring	4	Unprotected spring	5	Surface water	6
Rainwater	7	Bottled/bagged	8	Tanker truck	9
Tap at house	10	Tap not at house	11	Other:	99

Q38. Approximately how long ago was this water collected?

	Hrs
	Days
I don't know	88

Q39. May I have a cup of drinking water?

Yes	1	No/Refuse *[Go to Q50]*	0

Q40. **OBSERVE: How was water retrieved?**

Pouring	1	Tap	2	Dipping	3

I am collecting a sample for bacteria analysis and a sample for metals testing in in the laboratory. I'm also testing for temperature, pH, and electrical conductivity. ***Use probe methods to measure sample.***

Q41. ***Record Temperature*** ℃ Q42. ***Record pH*** Q43. ***Record EC***

Q44. Did you or someone in your household do anything to make this water safe to drink?

Yes	1	No *[Go to Q44]*	0
I don't know *[Go to Q44]*			88

Q45. How did you treat this water?

Ceramic filter	1	Biosand filter	2	Sawyer filter	3
Lifestraw filter	4	SODIS	5	Chlorine	6
Boiling	7	I didn't treat it	8	I don't know	88
Other:					99

Q46. Approximately how long ago was this water treated?

	Hrs		Days
		I don't know	88

Only answer Q47 and Q48 if respondent said they treat with chlorine. If not [Go to Q49]

Because the water was treated with chlorine, I am going to measure the chlorine.

Q47.	***Record FCR***		ppm (mg/L)	Q48.	***Record TCR***		ppm (mg/L)

Q49. Is this water managed by the Water Committee?	Yes	1	No	0	I don't know	88

I am now going to ask you questions about the DWSSP program

Q50.	Have you heard about the DWSSP program?	Yes	1	No *[Go to Q51]*	0	I don't know *[Go to Q51]*	88
Q51.	Have you heard about the village Water Committee?	Yes	1	No *[Go to Q52]*	0	I don't know *[Go to Q52]*	88
Q52.	Have you heard about the Village Plumber?	Yes	1	No ***[end]***	0	I don't know ***[end]***	88

Q53. What has the DWSSP Program or Water Committee taught about sanitation?

Build a latrine	1	Emptying schedule	2	Use ash	3
Keep latrine clean	4	Roof and walls	5	Empty latrine	6
Other:					99

Q54. What has the DWSSP Program or Water Committee taught about handwashing?

Build a station	1	Use soap	2	Use ash	3
Scrub for 1 min	4	Scrub under nails	5	Dry on clean towel	6
Other:					99

Q55. What has the DWSSP Program or Water Committee taught about drinking water?

Keep source clean	1	Keep animals away	2	Wash container	3
Fix tap / draw	4	Treat water	5	Cover container	6
Use clean dipper	7	Serve in clean cup	8	Get fresh water	9
Other:					99

Q56. Can you please explain what work the Water Committee does in the community?

Q57. Can you please explain how you communicate with the Water Committee or Plumber if you notice a problem?

Q58. Can you please explain what damage was done to the water supply after TC Pam and how it was fixed?

Q59. Can you please explain how the village water supply was effected by El Nino and how that changed your collection and use of water?

Q60. Can you please explain what a Drinking Water Safety and Security Plan is?

Q59. Record type and score for sanitary survey at point of collection: ***Type*** ______ ***Score*** ______

Thank you very much for your time!

Annex B – Focus Group and Key Informant Surveys

Number	

Key Informant Interview

A	Enumerator Name		
B	Date and Time of Interview	Date:	Time:
C	Province		
D	Island		
E	Name of the Village		
F	GPS Coordinates	N:	W:

Q1. **(Circle respondent's sex)**

Male	1	Female	0

Q2. How old are you?

	yrs

Q3. Did you go to school?

Yes	1	No *[Go to Q5]*	0

Q4. What is the highest grade you completed?

	grade

Q5. Can you read?

Yes	1	No	0

Q6. Where do you live?

Q7. How long have you lived there?

Native	1		yrs

Q8. What would you say are the biggest health problems that the community faces today?

Diarrhea	1	Headache	2	Chest pain / heart	3
Blood pressure	4	Cough / respiratory	5	Stomach / abdominal	6
Fever	7	Malaria	8	Cholera	9
General pain	10	Cold / Flu	11	Other:	99

Q9. What ways do you know to prevent diarrhea / cholera?

Drink safe water	1	Wash hands	2	Use latrine	3
Cook food	4	Peel vegs / fruit	5	Cover food	6
Clean house	7	Clean dishes	8	Don't know	9
Other:					99

Q10. What is your role in the DWSSP program?

Water Comm. *[Go to Q23]*	1	Plumber *[Go to Q57]*	2
Training Org. *[Go to Q54]*	3	Local Gov *[Go to Q49]*	4
Chief/Village Gov *[Go to Q11]*	5	Medical Prof. *[Go to Q57]*	6
Other [Go to Q11]:			99

Chief or Member of the Village Governance OR "Other" ONLY

Q11. Please describe your role in working on water, sanitation, and hygiene issues in the community:

Q12. Please describe your role in interfacing with the Drinking Water Safety and Security Plan Water Committee:

Q13. Please discuss what has been successful in community outreach and education accomplishments on water, sanitation, and hygiene (types of events, information, number of beneficiaries, feedback from community):

Q14. Please discuss challenges in community outreach and education on water, sanitation, and hygiene (types of events, information, number of beneficiaries, feedback from community):

Q15. In what ways do the community participate in water, sanitation, and hygiene projects (design, implementation, funding)?

Q16. Please discuss what the community likes about any of these implmented projects (which aspects?):

Q17. Please discuss what the community does *not* like about any of these implemented projects (which aspects?):

Q18. From where did you feel like the community received good support in carrying out these projects (training, funding)?

Q19. From where would you have liked more support in carrying out this project?

Q20. What would you say are some of the biggest challenges for the Water Committee?

Q21. What would you have done/recommended be done differently in the way the Water Committee functions?

Q22. What would you say are some of the key things that need to be addressed to ensure continuity of water projects?

Water Committee ONLY:

Q23. How many people use the water supply? [ ]

Q24. What is the type of source for the water supply?

Closed well	1	Open well	2
Protected spring	3	Unprotected spring	4
Rainwater	5	Canal	6
Surface water	7	Other:	99

Q25. Is the water piped to the community?

Yes	1	No	0	Don't know	88

Q26. Is their motorized pumping in the system?

Yes	1	No	0	Don't know	88

Q27. Does the system have central water storage reservoirs?

Yes	1	No [*Go to Q29*]	0	Don't know [*Go to Q29*]	99

Q28. How many water storage reservoirs are in the system? [ ]

Q29. Does the system consist of tap stands?

Yes	1	No [*Go to Q32*]	0	Don't know [*Go to Q32*]	99

Q30. How many public tap stands? [ ] Q31. How many private tap stands? [ ]

Q32. Is the water treated by the Water Committee?

Yes	1	No [*Go to Q34*]	0	Don't know [*Go to Q34*]	99

Q33. How was this water treated?

Sedimentation	1	Filtration	2	Flocculation	3
Chlorination	4	UV Disinfection	5	I don't know	88
Other:					99

Q34. How is the water supply system managed?

Community (eg Water Committee)	1	No management	2
Local government / municipality	3	Other:	99

Q35. What year was the Drinking Water Safety and Security Plan made? [ ]

Q36.

Who is on the Water Committee? - *Is membership documented?* - *Are all people with responsibility for water supply on the team?* - *Are relevant supporting organizations involved?* - *Is their gender balance on the team?*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q37.	When does the Water Committee meet? - *Does the team meet regularly?* - *Are team meetings and outcomes documented in some way?* - *Is there evidence that the VWSS is a continuously used process?*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q38.	How are different water sources in the community being used? - *Are all sources documented?* - *Is it clear which sources are used for different types of needs?* - *Is seasonality of the supply documented or managed?* - *Are sources documented by the block?*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q39.	Can you show me a map of your water system? - *Is it clear and up to date?* - *Are all major parts of the supply system included?*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q40.	What information do you have about your water supply system? - *Has the Committee walked source to tap? When?* - *Are all steps of system been described?* - *Does the committee note how activities in the catchment impact the source?* - *Are HWTS practices understood?* - *Has the Committee collected info related to water supply (WQ, manuals)*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q41.	How have you identified events that threaten your water supply? *- Does the Committee understand this step is to identify what could go wrong* *- Are hazards documented for all steps* *- Did the Committee consider what has gone wrong in the past and taken efforts to minimize in the future?* *- Have the most relevant hazards been considered, inc. sanitation?*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***
Q42.	How have you decided which of these events are the most important? *- Have the hazardous events been ranked / prioritized via risk assessment* *- Were existing control measures identified/considered in risk assessing* *- Is risk assessment complete, logical, appropriate and sensible?* *- Is it clear which hazardous events are most important and require attention*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***
Q43.	What system improvements are needed? *- Have improvements been identified for all significant risks, inc. those requiring support/funding from outside village?* *- Is an improvement plan documented?* *- Does the plan clearly describe what, who, when should be done, and its cost* *- Does the plan include non - infrastructure improvements?* *- Are improvements carried out?*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***
Q44.	How and when does the Water Committee check all parts of the water system? *- Do they regularly inspect structure and activities close to the source?* *- Do they regularly monitor quality?* *- Is there a monitoring/inspection plan?* *- Does the plan address what will be done if something is wrong?* *- Are all important control measures included in the monitoring/inspection*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q45.	How often is your water quality being tested by others? *- Is their water quality regularly tested by the health office?* *- Are the results of external testing made available to the Water Committee?* *- Do the results indicate non-compliance ?* *- Is the schedule for external WQ tests documented and progressing as planned*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q46.	What instructions are available to the maintainer / Committee to follow? *- Are there clear written or pictoral instructions to guide important to guide operation and maintenance?* *- Are instructions clear and easy?* *- Does the Water Warrior understand these instructions and apply them in practice*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q47.	What will you do in case of a water quality incident or emergency? *- Has the Committee considered what to do in case of water quality incident?* *- Has a response plan been documented*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Q48.	When was your Drinking Water Safety and Security Plan updated? *- Is the plan regularly reviewed and revised?* *- Is it up to date?*	***Document Strengths:***	***Document Improvement Opportunities:***	***Document follow-up actions made by committee:***

Local Government Official ONLY:

Q49. Please describe how your role fits into the local water supply structure:

Q50. Please describe the training you may have received on water supply and management (who provided, quality, topics):

Q51. Please describe your role in working with the DWSSP program in the community: (frequency of visits, types of interactions with community, trainings given, etc):

Q52. Please describe the ways in which the Water Committees may have come to you for assistance and what was provided:

Q53. Please describe the challenges of your job:

Training Agency Facilitator ONLY: ***Note agency:***

Q54. Please describe what your role is in working with the community on DWSSP:

Q55. Please describe the training you have received (who provided it, quality, what you learned):

Q56. What are the most challenging aspect of the DWSSP program to implement?

Village Plumber ONLY:

Q57. Please describe how you were chosen to be the Village Plumber:

Q58. Please describe the training you have received (who provided it, quality, what you learned):

Q59. Please describe your job tasks and how often you accomplish them:

Q60. Please describe how to get your materials for repairs, upgrades, etc:

Q61. Please describe what you do when you there is a major repair beyond your capabilities:

Medical Professional ONLY:

Q57. What medical subdivision does the community come under? [ ]

Q58. What medical area does the community come under? [ ]

Q59. Name of the nearest health center? [ ]

Q60. How many households does the community have? [ ]

Q61. What is the total population of the community? [ ]

Q62. Is diarrhea a problem?		Yes	1	No *[Go to Q64]*		0	
Q63. Compared to normal?	Less	1	Same	2	More	3	
Q64. Is nausea a problem?		Yes	1	No *[Go to Q66]*		0	
Q65. Compared to normal?	Less	1	Same	2	More	3	
Q66. Is vomiting a problem?		Yes	1	No *[Go to Q68]*		0	
Q67. Compared to normal?	Less	1	Same	2	More	3	
Q68. Is abdominal pain a problem?		Yes	1	No *[Go to Q70]*		0	
Q69. Compared to normal?	Less	1	Same	2	More	3	
Q70. Is prolonged fever a problem?		Yes	1	No *[Go to Q72]*		0	
Q71. Compared to normal?	Less	1	Same	2	More	3	

Suspected Waterborne Diseases

In the last month:

Q72. Are any suspected cases of Typhoid being investigated? | Yes | 1 | No *[Go to Q74]* | 0 |

Q73. Number of Typhoid cases being investigated: [ ]

Q74. Are any suspected cases of Leptospirosis being investigated?	Yes	1	No *[Go to Q76]*	0

Q75. Number of Leptospirosis cases being investigated: ______

Q76. Are any suspected cases of Hepatitis A being investigated?	Yes	1	No *[Go to Q78]*	0

Q77. Number of Hepatitis A cases being investigated: ______

Confirmed Waterborne Diseases

In the last month:

Q78. Is Typhoid a problem?	Yes	1	No *[Go to Q80]*	0

Q79. Number of confirmed Typhoid cases: ______

Q80. Is Leptospirosis a problem?	Yes	1	No *[Go to Q82]*	0

Q81. Number of confirmed Leptospirosis cases: ______

Q82. Is Hepatitis A a problem?	Yes	1	No *[Go to Q84]*	0

Q83. Number of confirmed Hepatitis A cases: ______

Q84. Record sanitary risk score for the source: ______

Thank you very much for your time!

Annex C – Preliminary Ceramic Filter Imaging with Wood's Metal

Prior to access to an x-ray micro-CT, we attempted to image the ceramic filter samples by first intruding them with Wood's metal.

Ceramic filter sample cores, 12 mm in diameter and the length of the through-thickness of the filter wall, were cut from the four filter samples in this study. They were baked dry and then loaded into a casting chamber and placed under vacuum to evacuate the pore spaces. Under argon gas from 170-413 kPa, the cores were then intruded with Wood's metal, a low-melting temperature (70 °C) solder alloy of bismuth, lead, tin, and cadmium. Prior to intrusion, the Wood's metal was melted by placing the casting cup in boiling water, and allowing the boiling water to transfer heat through the cup to the alloy.

An aluminum vacuum chamber casting cup was designed and machined at Tufts (Figure C-1) such that the top and bottom casting cups separated to allow new samples to be set-up inside. The top casting cup contained an attachment for the vacuum and gas lines as well as the thermocouple. Inside the casting cup was an assembly consisting of stacks of square o-rings and rubber membranes cushioning the cylindrical sample. The o-rings were designed as the support system because the number utilized in the set-up could be changed depending upon the thickness of the sample. Furthermore, the o-rings were insulating such that the Wood's metal did not come in contact with the aluminum walls of the casting cups.

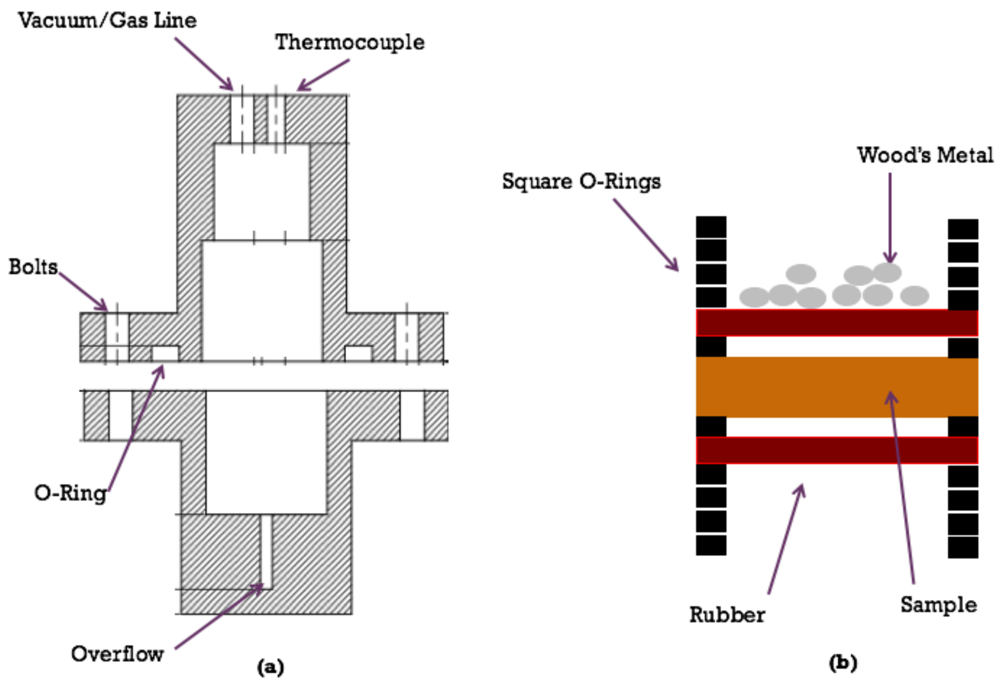
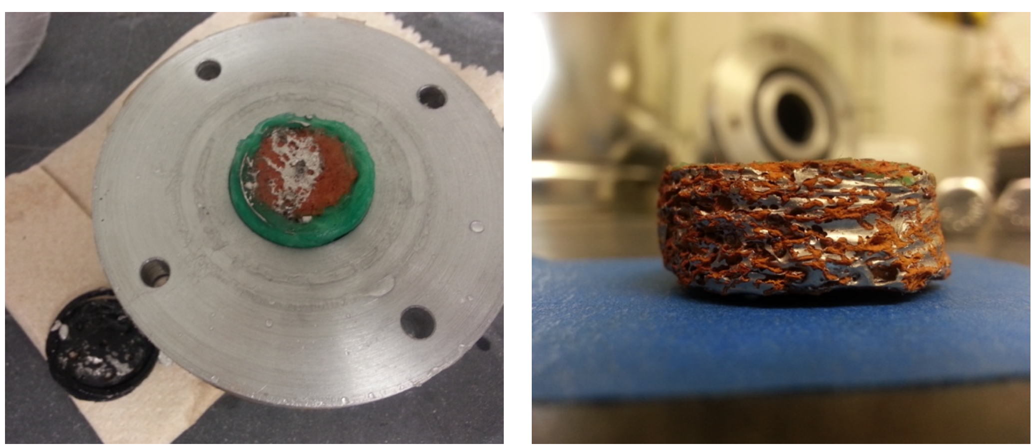


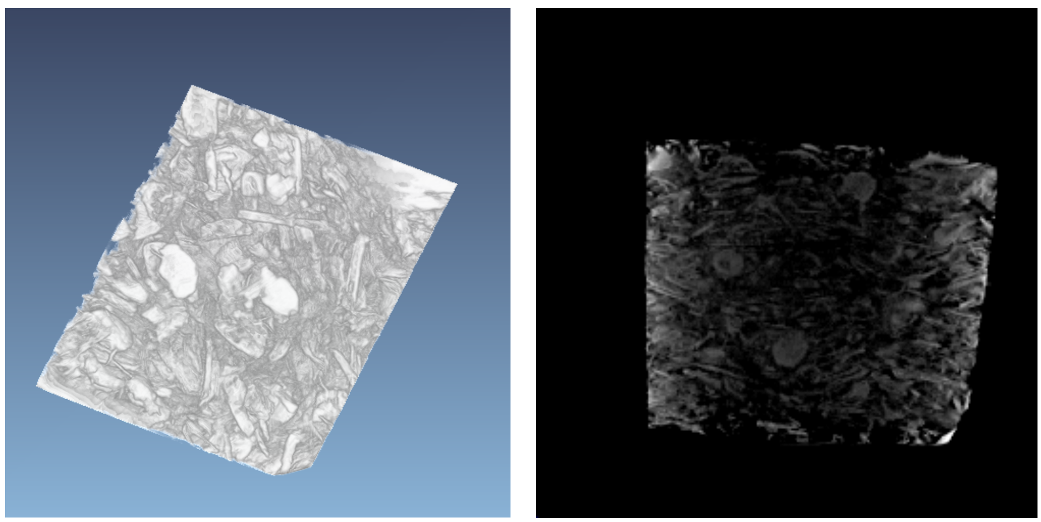
Figure C-1: Wood's metal intrusion equipment: (a) casting cup design; (b) internal configuration of sample intrusion



(a) **(b)**

Figure C-2: Results of Wood's metal intrusion: (a) surface of sample sitting inside bottom casting cup; (b) intruded sample core viewed from the side

Wood's metal intruded the large macropores fairly well, but a 413 kPa limit on the gas pressure meant that there were still smaller pores that were not intruded (Figure C-2). Intruded samples were taken to the Electrical, Electronic and Electromechanical Parts Engineering and Analysis team at NASA Marshall Space Flight Center in Huntsville, Alabama for imaging in a GE phoenix microme|x Microfocus X-ray with 3D CT.



(a) **(b)**

Figure C-3: CT scans of intruded filter samples: (a) 3D view of pores reproduced as solid images; (b) reconstructed pore space, pores on the edges were intruded better than pores in the middle and thus were more visible in imaging

Images of the intruded samples were collected at 100 keV using a copper X-ray filter with an x-y resolution of 10.9 μm/pixel and a resolution in the z-direction of 50 μm/pixel, which was the distance between slices in the stack (Figure C-3). Imaging resolved the Wood's metal cast of the macropores well as the density of the Wood's metal was sufficiently different from the ceramic and from air.

However, imaging of un-infiltrated samples was poor due to difficulties in resolving the difference between air and ceramic. In combination with the poor resolution for nano- and micropores in the range of interest for filtration, the ability to resolve the porosity without the Wood's metal, and the limit of 413 kPa maximum on gas pressure, this method was poor for characterizing anything smaller than the macropores.

This work was completed with the help of Jim Hoffman (machining) and Dr. Terry Rolin (CT imaging at NASA).