The Effectiveness and Suitability of Slow Sand Filters to Treat Canadian Rural Prairie Water

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Abstract

Traditional slow sand filters (SSFs) were inexpensive, reliable and chemical-free, but required laborious and time-consuming maintenance and relatively high quality influent water. Renewed interest in SSF systems as low maintenance, effective water treatment for small communities has resulted in enhanced plant and filter design, improved operating procedures for increased efficiency and expanded range of acceptable raw water quality input. Challenges with SSF technology associated with the cold weather conditions in the Canadian Prairie climate may impair performance, especially during the ripening stage. Despite some limitations to the use of SSFs, recent design modifications and improvements for operation and maintenance of SSFs have expanded the potential application of the technology to a broader range of contaminants in highly variable environmental and operating conditions. The flexible and modular design options inherent to SSF systems, along with the modifications in expanded application, make SSFs highly attractive for potable water treatment in rural and remote regions.

Key Words: Slow sand filtration, rural water quality, potable water treatment, biological activated carbon filtration

Introduction

In small rural and remote communities across Canada there is an identified need for cost-effective and reliable potable water treatment. Lippy and Waltrip (in Cleary, 2005) reported that rates of non-compliance to drinking water standards are directly correlated to decreases in the size of populations served. Source water in rural areas is typically of poorer quality than that in urban centers where development of and access to more sophisticated water treatment infrastructure and skilled operators is possible. Conventional treatment technologies available to rural communities tend to be too expensive, complex and labour intensive for most rural communities and may not perform as consistently when scaled down (Cleary, 2005). Slow sand filtration (SSF) has attracted attention as a potential solution to these types of rural water quality and treatment challenges due to its low capital and operating costs, ease of operation, reliability and minimal requirements for maintenance and labour (Logsdon et al., 1990; Huisman & Wood, 1974).

Conventional Slow Sand Filtration Operation and Maintenance

Although SSF has been used since the 19C and its ability to treat water efficiently is not in doubt, its application waned with the development of modern technologies. Ironically, one of the most significant advantages of SSF, its simplicity, also lends the misperception of it being an irrelevant and out-dated technology.

Traditionally, SSFs were installed to provide removal of microorganisms in existing chlorine disinfection plants using relatively high quality raw water. Stand alone SSF systems are not recommended for influent water with turbidities greater than 5 NTU since filter clogging and subsequent decreased filter run length result in frequent cleaning (Logsdon et al., 2002). In addition to turbidity, source water quality parameters for application of SSF without pre-treatment or GAC/BAC include low chlorophyll *a* (< 0.05μg/L), iron and manganese concentrations of less than 0.3 and 0.05 mg/L, respectively, minimal dissolved heavy metals, pesticides, and color compounds, and no oxidant residual prior to filtration (Logsdon et al., 2002). SSF systems operate best for non-clay-bearing water sources (Cleary, 2005).

SSF are open vessels partially filled with media - typically fine sand. Raw water flows into the top of the filter where it is retained above the sand bed for a significant period of time to allowing particle settling. The water percolates slowly through the sand bed to allow biological activity and purification by a variety of physical, biochemical and biological processes within the sand bed (Visscher, 1990; Weber-Shirk & Dick, 1997a). Conventional SSFs have a slow filtration rate (0.1-0.3 m/hr) with no chemical pretreatment and long filter runs (Campos et al., 2002; Collins et al., 1991). Beds are cleaned by scraping, washing and resanding, but since the formation of a *schmutzdecke* is a required operational element no filter backwashing may occur to disturb this biofilm layer. Additionally, the sand in SSFs is of uniform grain size (0.1-0.3mm) at all depths (Campos et al., 2002).

In operation, biological growth develops within the sand bed and gravel support layer. A thin layer of inert biological material called the *schmutzdecke* forms on the bed and assists in treatment by produces natural polymers to reduce turbidity and reducing biological contamination through predation (bacterivory) (Logsdon et al., 2002; Weber-Shirk & Dick, 1997a, Bellamy et al., 1985). Physical straining and physical/biochemical sorption processes remove particles from the raw influent water (Weber-Shirk & Dick, 1997b). It has been suggested that particle size plays a significant role in determining the dominant treatment process. Weber-Shirk and Dick (1997a) suggest physical-chemical mechanisms are significant for particles between 0.75 and 10 µm while biological processes are important for particles in the 0.75 – 2 µm diameter range.

To initiate SSF systems, raw water flows through the filters to waste until the biological communities have matured for adequate treatment efficiency ("ripening"). Both biological and physical-chemical ripening occur to develop biological activity and straining and adsorption mechanisms respectively (Weber-Shirk & Dick, 1997a). Physical-chemical particle removal is more efficient when particles are already deposited in the sand bed due to enhanced adsorption of influent particles to retained particles (Weber-Shirk & Dick, 1997b). Biological development is less predictable as it depends on several factors including pH, temperature, available organic nutrients, filtration rate and raw water quality. Biological development may occur over several days or may require several months to occur.

Maintenance of SSFs is required when significant headloss occurs, and thus reduced treatment efficiency occurs. The SSF is drained and the top layer of sand and *schmutzdecke* (approximately 15 cm) removed in a process called scraping. Scraping temporarily reduces filter efficiency while a mature *schmutzdecke* again develops (Huisman & Wood, 1974). After several scrapings, the filter media may be reduced to its minimum bed depth and require resanding with either new or cleaned filter media added to the bed.

Conventional SSF Performance

SSF has proven efficient for removing many types of microbial, chemical and physical impurities in raw water sources (Table 1). However, chemical parameters such as sulphate (SO_4^{2-}), nitrate (NO_3^-), sodium (Na^{2+}), total dissolved solids (TDS), calcium (Ca^{2+}), magnesium (Mg^{2+}) and hardness ($CaCO_3$) are not treated effectively by SSF systems on their own. For instance, raw water that contains high concentrations of ammonium will likely exceed water quality guidelines for nitrate concentrations since biological treatment converts ammonium (NH_4^+) to NO_3^- (Peterson & Corkal, 1997).

Advantages and Challenges

SSF systems can effectively provide comprehensive multi-barrier treatment for a variety of physical, chemical and microbiological water quality challenges. SSFs are uncomplicated technology requiring little process adjustment and, therefore, also requiring reduced expertise and time for operation, maintenance and monitoring (Logsdon et al., 1990; Visscher, 1990; Bellamy et al., 1987). On the whole, SSFs are relatively inexpensive to operate (Logsdon et al, 1990). There are no chemical inputs, minimal chlorine required for residual (Amburgey et al, 2006) and maintenance and energy requirements are low due to gravity flow operation (Cleary, 2005). Few residuals are produced from SSF water treatment systems, except when the filter requires scraping, a dirty sand residual may result (Logsdon et al., 1990). Furthermore, very little water is wasted during the filter cleaning procedure (Cleary, 2005), thus preserving source water quality and not increasing the lagoon volume required to handle waste effluent.

The most obvious disadvantage of SSF is the comparably large footprint required which, in cool climates, requires enclosure and heating. Although SSFs can produce very good quality water, they cannot remove some contaminants including sulphate, nitrate, hardness, (Peterson & Corkal, 1997) and fine, stable colloidal matter (Cleary, 2005). Further disadvantages of SSF technology include laborious and time-consuming filter scraping and resanding procedures requiring downtime for re-ripening. When a raw surface water source containing high turbidity and algal content is used, frequent filter cleaning may be required to prevent clogging and headloss (Logsdon et al., 2002). Surface waters may pose a particular challenge to conventional SSFs as they are typically prone to sudden fluctuations in quality characteristics that may upset the biological activity and affect filter efficiency (Huisman & Wood, 1974)

Many researchers have documented the affect of cooler temperatures on SSF functionality. Microbiological and organics removal rates are known to be affected by lower temperatures (Moll et al., 1999; Juhna & Melin, 2006; Logsdon et al., 2002; Melin et al., 2001; Huisman & Wood, 1974). Moll et al. (1999) noted significant reduction in the removal of natural organic matter (NOM) by a biosand filter operated at 5°C in comparison with those operated at 20°C and 35°C. Alternatively, Liu et al. (in Juhna &

Melin, 2006) noticed that removal of organics was not as significantly impacted by low water temperatures as expected. It was hypothesized that an abundant and active biomass can buffer operational changes and, at lower temperatures, biodegradation occurs along the bed depth rather than being confined to the top of the filter (Juhna & Melin, 2006). This observation supports that of Melin et al. (2001) who noted that although total organic carbon (TOC) removal followed seasonal variation with higher removals in the summer, efficiency decreased gradually in cooler temperatures. Although Schuler et al. (1991) observed virtually no microbial growth in a filter receiving influent water between 4 and 8°C, a study conducted by Mauclaire et al. (2006) documented a diverse community of microorganisms colonizing SSFs operating at the same winter temperatures. They concluded from these results that the microbial populations were well adapted for the operating conditions.

Along with cold temperatures, limited available nutrients for biomass growth and maintenance is thought to hamper biofilter performance in northern climates (Melin et al., 2001). Phosphorus and nitrogen are key inorganic nutrients for microbial growth and in water with excessive organic carbon, these nutrients can become limiting (Juhna & Melin, 2006). Melin et al. (2001) found unexpectedly that TOC removal was not significantly reduced by limited phosphorus concentrations. They hypothesized that phosphorus is released from dead cells when the filter reaches a pseudo-steady-state. Vahala et al. (in Melin et al., 2001) observed no difference in removal efficiency for two granular activated carbon (GAC) filters in an experiment during which one filter was fed with phosphorus spiked water. Although nutrients can be limiting in certain source water supplies, it has been shown that adequate nutritional requirements can still be achieved to sufficiently support and sustain biological growth under a variety of SSF conditions.

Intermittent operation of biological filters has been a historical operational constraint as it is thought to be harmful to filter functionality. Allowing the filter to achieve steady-state and reducing the potential for anaerobic activity in the filter are both affected by intermittent flow regimes (Huisman & Wood, 1974; Logsdon et al., 2002). Since the microorganisms are limited by the amount of organic matter in the raw water, cell growth and cell death reach an equilibrium state at which organic matter is released and made available to microorganisms deeper within the filter. In this way the filter achieves a steady-state of biological growth and biodegradation of organic matter (Huisman & Wood, 1974). When the flow is stopped, and even if the sand bed remains submerged, the stagnant water may become depleted of dissolved oxygen and nutrients required for biological activity, thus compromising the viability of the microbial populations throughout the filter. In their study of the effects of shutting down biologically activated carbon beds, Niquette et al. (1998), observed a drastic reduction in dissolved oxygen from 10 to 2 mg/L within a couple of hours, well below the suggested 3mg/L minimum (Huisman & Wood, 1974). The near-anaerobic conditions reduced the overall fixed bacteria density in the filter. However, the effect was less pronounced at lower water temperatures where the microbes are already less active. Despite the observed reduction of biomass after shutdown, Niquette et al. (1998) demonstrated little effect on produced water quality. Both DOC and ammonia biodegradation rates were remained constant at pre-shutdown removal efficiency after filtration was resumed 24 hours later.

Traditional SSFs are built outdoors and are open to the environment. However, their use in northern climates, such as Saskatchewan, necessitates covering or placement indoors for protection from freezing. Open SSFs receive substrate inputs from the environment as well as the raw water and have the advantage of potential beneficial interaction with external organisms such as aquatic insects that can remove matter from the water column. In a study comparing biomass development in covered and uncovered SSFs, Campos et al. (2002) documented that covered biomass accumulated at a slower rate than that of the uncovered filter. Additionally, the covered biomass was not as dense or thick at its maximum as compared to the uncovered filter. Despite these biomass differences, though, no differences in effluent quality or TOC and DOC removal rates were noted. The researchers concluded that, since no difference was observed in water treatment performance, filter covers may actually be beneficial for limiting the amount of biomass and, thus reducing headloss and clogging potential.

Modifications to Conventional SSF Technology

The renewed interest in SSF technology to fulfill the demand for uncomplicated, effective water treatment for small, rural, and remote communities has resulted in several new design and operational concepts related to both the treatment plant and the filters themselves. These design modifications increase not only treatment efficiency, but also expand the range of raw water that can be treated. As a result, SSF has evolved into a robust process that can operate within a broad range of water quality and operating conditions with minimal process adjustment (Cleary, 2005).

The pretreatment design modifications are an example of how SSF technology has evolved over recent years. Pretreatment extends filter runs and preserves the integrity of the biological filters. SSF systems benefit from pre-oxidation using ozone in place of traditional chlorine chemical additions that could damage the biological growth (Logsdon et al., 2002). Application of ozone can facilitate the removal of NOM and colour by SSFs by breaking up large organic molecules into smaller material that is more bioavailable (Logsdon et al., 2002). Ozonation can also improve performance of SSFs in cold temperatures. Seger & Rothman (in Logsdon et al., 2002) reported that TOC removal was increased by use of pre-ozonation in water warmer than 8°C and even further increased at cooler temperatures.

Other pretreatment modifications, such as roughing filters composed of course gravel media, can reduce solids loading on the sand filters, increase the filter run length, allow operation at higher hydraulic loadings and improve overall effluent quality (Cleary, 2005). Roughing filters can be designed as upflow, downflow, or horizontal flow and are considered to be simplistic in design, operation and maintenance. Depending on design, roughing filters can handle turbidity in the range of 50 to 200 NTU and spikes as high as 500 to 1000 NTU (Ochieng et al., 2004). The use of a roughing filter also increases performance of the slow sand systems in cold water conditions by providing additional biological activity and increased retention time to compensate for any loss of efficiency downstream in the system (Logsdon et al., 2002). A similar concept, the pebble matrix filter (PMF), consists of large pebbles infilled with a mixed layer of sand and pebbles. The PMF is most applicable for high suspended solids water sources and has been proven efficient for removal of suspended solids throughout the 25 to 5000 mg/L range (Rajapakse & Ives, 1990).

Another design modification in modern SSFs include the addition of GAC filters to provide “polishing” or removal of contaminants including organics, taste and odour compounds, pesticides, herbicides, trihalomethane (THM) precursors, and ozonation by-products (Cleary, 2005). GAC has a very high adsorption capacity for many pesticides, so is commonly applied for removal of these compounds from potable water (Heijman & Hopman, 1998; Hopman et al., 1994). GAC filters in slow sand systems also develop biological activity and can be referred to as BAC (biologically activated carbon). Addition of pre-ozonation and GAC filtration to SSFs provide consistently better treatment results than SSF alone and are highly suitable for northern climes (Galvis et al. in Cleary, 2005).

The term multistage filtration (MSF) has evolved to describe SSF combined with a pretreatment phase, particularly in reference to ozonation and roughing filtration. MSF has attracted attention worldwide due to its proven ability to produce high quality potable water from substantially polluted sources (Ochieng et al., 2004). A study comparing the performance of MSF and conventional treatment concluded that, in general, the MSF treatment units performed better than conventional systems for both suspended solids and turbidity removal by a small but statistically significant margin. The MSF systems also greatly improved the bacteriological quality and required lower disinfection than the conventional train (Ochieng et al., 2004). A number of studies have been conducted to describe the performance of multistage slow sand systems (Table 2).

Other options to extend filter runs include *in situ* modifications to the filters. Mbwette et al. (1990) examined the application of non-woven synthetic fabrics to the surface of the sand bed for increasing SSF performance. The results indicated that placement of an appropriate fabric type and thickness can extend a filter run by a factor of 3-5. The fabrics offer further advantages including minimal disruption to filter hydraulics, no requirement for scraping and cleaning sand, and ease of washing and replacing fabric. The feasibility of removing, cleaning, and replacing fabrics on filters larger than 30 m^2 has not been examined to date. For the time being, the use of bed surface fabrics are limited to small-scale treatment facilities.

SSF Maintenance

Since cleaning SSF systems is a labour-intensive and time consuming endeavor several mechanized and hydraulic systems have evolved to simplify the procedure. One popular mechanized filter cleaning method is “wet-harrowing”, which involves raking the top layer of the filter while draining off the debris laden supernatant from the top of the filter. Harrowing redistributes *schumtzdecke* microorganisms deeper into the filter rather than removing them reducing downtime for re-ripening. The wet harrowing method must be completed with care to ensure that disturbance of the *schmutzdecke* does not cause contaminant breakthrough. The results of a study by Eighmy et al. (1992) using three SSF facilities indicated that harrowed *schmutzdecke* had a greater number of actively respiring bacteria and, therefore, performed better with respect to both TOC and THM precursor removal. The researchers hypothesized that harrowing encourages maintenance of bacterial populations that are better adapted to metabolize the biodegradable portion of assimilable organic matter (Eighmy, et al., 1992).

Hydraulic cleaning of SSFs has also been applied as a very rapid process with low-labour requirements. The operational constraints are related to maintaining a low wash water velocity while backwashing so that only minimum bed expansion, a low degree of scouring, and reduced disturbance of subsurface biologically active layers occur (Huisman & Wood, 1974). The method does have a few disadvantages including the redistribution of finer sand grains to the surface of the filter promoting more frequent clogging and shorter runs. However, well-graded sand can be used to circumvent this problem (Huisman & Wood, 1974).

Another innovative SSF cleaning and resanding method, trenching, reduces effects on filter efficiency and the need for lengthy re-ripening periods (Collins et al., 1991; Huisman & Wood, 1974). This method involves moving the remaining sand to one side, adding new sand, and then replacing the old sand on top of the new layer. In this way the microorganisms are retained at the top of the filter where they can quickly resume their function.

SSF Construction

Slow sand filters are constructed from materials other than the traditional poured concrete. Molded polyethylene structures are being used increasingly for this application and offer distinct advantages to small communities. The cost of polyethylene filters is less than concrete, they can be certified non-toxic, and do not require testing as do individual concrete installations (Blackburn, 1997). The use of preformed filters also allows for modular design that can be expanded in response to capacity increases and can simplify the engineering and design requirements for treatment train development.

Modifications to the design, operation and maintenance of slow sand filters have expanded the effectiveness of SSFs for treating a wider range of contaminants in highly variable environmental and operating conditions. These modifications, combined with the inherent advantages of SSF have promoted it as an attractive alternative to small northern communities. Within the past few years, regulatory authorities in the Canadian prairies have approved SSF systems for use by municipalities. Several small-scale treatment facilities in the prairies that could not meet water quality guidelines have installed slow sand filter plants.

Case Studies

The SSF potable water treatment systems for two Saskatchewan, Canada communities were evaluated for design and operational efficiency, potable water production quality and quantity. Both communities are located in rural, southern Saskatchewan and have populations of less than 50. Community A relies on a surface water reservoir while Community B uses a groundwater source for its potable supply.

Community A

In early 2005, Community A in Saskatchewan installed a 11.4m^3/d biological filtration plant for improving the treatment efficiency of reservoir water, particularly for turbidity and THMs. The biological filtration plant consists of ozone pre-treatment, clarification, biological slow sand filtration, and biological activated carbon (BAC) filtration. A down flow roughing filter replaced the settling tank in spring 2007. The system is gravity fed at 0.24m/h. The ozone contacting system is composed of an air-fed 4g/hour corona discharge ozone generator producing an ozone dose of 7mg O_3/L injected into a 66cm contacting tank. The biological sand filter contains a layer of pea gravel overlain with silica sand (effective size 0.45-0.55mm), to a total bed depth of 1.02m in a 1.75m polyethylene tank. The BAC filter has a total bed depth of 1.23m including a base layer of gravel, followed by layers of sand and carbon.

The system requires minimal maintenance and filters are clean-in-place style that does not require scraping or resanding. Instead, the cleaning involves a light air scour and low-rate upflow wash with unchlorinated filtered water. This method loosens and removes a small portion of the *schmutzdecke* meaning that minimal re-ripening is required.

Bacteriological quality is controlled through turbidity and natural SSF bacterivory processes. Turbidity has been closely monitored from commissioning to present day to assess treatment efficiency (Figure 1). The time of commissioning (March 2004) is visible since turbidity in the effluent exceeds that the raw water. The SSF provides exceptional turbidity removal at an overall average of 93%, regardless of seasonal variations in raw water conditions and influent turbidity even prior to the addition of the roughing filter.

A comparison of THM results pre- and post- SSF installation show that THM concentration was reduced from having 7 of 10 THMs greater than 100 μg/L to consistently achieving less than 100μg/L for all THMs (Figure 2). This operational efficiency was only lost during an anomaly in March 2007.

Bacteriological analyses indicate that microorganisms have not been present in the treated water since the plant's commissioning.

The only chemical addition to the treatment train is chlorine for disinfection and production of a distribution residual. On a daily basis, the operator needs 15 minutes to check chlorine and turbidity levels; on a monthly basis, the operator takes 2-3 hours for filter cleaning. Therefore, the total monthly operator commitment is between 9-11 hours.

Community B

In the winter of 2004 the Saskatchewan Community B installed a 11.4m^3/d biological treatment system to treat their well water. The previous treatment method, chlorination, was incapable of appropriately treating raw water that is consistently high in manganese and iron. The system consists of aeration, slow sand filtration, biological activated carbon filtration and chlorine disinfection. The system is gravity-based with a filtration rate of 0.24m/h. The biological sand filters are two 1.07m polyethylene tanks. The total bed depth of 1.06m consists of a base of gravel with a 76cm layer of sand, effective size 0.45-0.55mm. One similar sized activated carbon filter with a gravel base and a sand layer underneath a layer of activated carbon provides final polishing.

Although aeration was sufficient to oxidize iron, manganese continued to be problematic; therefore within a couple months of commissioning the aeration unit was replaced with ozone pre-treatment. The ozone contacting system is composed of an air-fed 4g/hour corona discharge ozone generator producing an ozone dose of 7mg O_3/L at average flowrate injected via mazzei injector into a 66cm contacting tank.

Turbidity analysis of finished water is shown in Figure 3. The ripening period at the beginning of January is characterized by high turbidities for approximately 20 days. Since the plant has been installed all bacteriological tests have showed no organisms present and average turbidity of the finished water, excluding the initial ripening period, is 0.10 NTU. The system successfully removes manganese bringing the concentration from as high as 0.8mg/L to below the acceptable limit of 0.05mg/L. Iron, typically slightly above 0.3mg/L, is consistently reduced to around 0.0017mg/L.

Daily operation requires about 10 minutes to check turbidities, chlorine and flow meters. The sand filters are cleaned every four weeks and the BAC filter every six months according to schedule rather than headloss. The filters are clean-in-place therefore time and labour commitment is minimal. Cleaning consists of draining down the supernatant on top of the bed, applying light air scour and upflow low-rate water wash with filtered, unchlorinated water. Each filter requires about half an hour to clean. The approximate monthly operator time commitment is around eight hours.

Barriers to Implementation

Considered an alternative treatment method with its fundamental mechanisms of treatment poorly defined for traditional water treatment designers (Campos et al., 2002), SSF is not wholly accepted by the engineering community as a viable technology. Resistance to prescribe this treatment may also be the result of some misconceptions as well. For example, biological systems to treat drinking water have been deemed unsafe by some due to the potential release of microorganisms from the filters. While it is true that some microorganisms are released due to sloughing of the biomass and transport on GAC fines, researchers such as Rickman & Huck, Bouwer & Crowe (in Sketchell et al., 1997) and Amburgey et al. (2006) have concluded that the released organisms are common species that are not pathogenic and do not pose a health problem. Also because many consulting engineers that are contracted by small communities are relatively unfamiliar with the principles and capabilities of SSF they are reluctant to suggest this treatment method or any other alternative technology, due to liability concerns. Regulatory agencies can also pose challenges. They tend to favour mainstream treatments and require considerable proof of ability to meet regulatory guidelines by non-conventional methods.

Conclusions

Despite organizational barriers, SSF is experiencing renewed interest as a result of its potential for application to small-scale systems. Significant advantages of SSF include simplicity of design, ease of operation and maintenance, cost effectiveness and reliability. New designs with additional unit processes such as ozone and roughing filter pre-treatment and BAC filtration have increased the range of raw water that can be treated with this technology. Innovative operational and maintenance techniques have made these systems suitable for small communities that have limited resources. Modified slow sand filtration systems have proven to produce exceptional quality water despite operating in cold temperatures, encountering a variety of contaminants, and in highly variable water conditions with minimal operating costs or maintenance making them a suitable alternative for small northern communities.

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