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Cost scenarios for small drinking water treatment technologies

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ABSTRACT

The objective of this paper is to present statistical models of costs based on new data obtained from manufacturers of a menu of treatment technologies suitable for small water systems. This analysis would be of interest to water management engineers and planners. We classify these technologies into six classes, depending on the contaminants removed. Our statistical results show that average costs (including capital, operating and maintenance) of production of these technologies depend on the flow rate as well as the number of contaminants removed. The larger the flow rate the lower the cost per volume treated and the more contaminants are removed, the higher the cost, for any given flow rate. One of our major finding is that for surface waters except those with high color and turbidity, UV-based treatment technologies can be cost effective. However, for any particular system, water engineers would take site-specific features into account to determine what technology is most appropriate.

Keywords: Costs of treatment; Small water systems; Disinfection; Economies of scale; UV; Ozonation

1. Introduction

According to the US Environmental Protection Agency [1], 94% of 156,000 public water systems in the US are small water systems, serving a population of less than 3,300 people. In Canada, the proportion of small systems in one survey was over 75% [2]. With a smaller tax base all small water systems face special challenges, unless the government aggressively supports small water treatment systems. In Canada many continue to encounter boil water advisories and even disease outbreaks. No doubt that with appropriate public funding, many of these problems can be reduced or eliminated. However, typically in North America, each small community or rural jurisdiction must cover its own capital and operating costs of their drinking water supply, although some jurisdictions offer a subsidy for capital costs. Often a rural community has a small population, lower average income and consequently a lower tax base. These financial constraints as well as other risk factors were highlighted at a 2004 Montana conference on small water systems [3]. These constraints are even more severe in developing countries.

Threats to public health persist in rural and small water systems even in the most advanced high income countries like the USA, Canada and Europe. What factors account for these waterborne disease outbreaks is

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outside the scope of this paper. The objective of this paper is to present statistical models of costs based on new data obtained from manufacturers of a menu of treatment technologies suitable for small water systems; this information would be of use to local government officials, water engineers and planners. Most of this paper is concerned mainly with plants that rely on surface water as the source.

For the USA, the American Water and Wastewater Association (AWWA) has published a number of reports that include recent water utility survey data on current disinfection practices and operations compared with practices in the late 1970s [4,5]. According to the AWWA 2008 report, chlorine gas remained the predominant disinfectant, used by 63% of respondents whereas those who used chloramine accounted for 30%; chlorine dioxide for 8%; ozone for 9%; and ultraviolet light (UV) for 2%. The comparable figures for Canada, are also available: according to the Environment Canada survey of Municipal Water and Wastewater Plants (2004), in Canada there were 2,402 drinking water systems in that survey, of which 1,513 reported a population of less than 3,000. Of these 1,513 drinking water plants, 136 gave information on the type of disinfection technology they use. Some 93% (127 out of 136) used chlorine as the only disinfectant. Those using UV or ozonation accounted for only 6% of the total. There is a potential for improving water quality by adopting newer technologies such as UV or ozonation and reducing the probability of waterborne disease outbreaks. At the same time there is an enormous market potential for corporations that can sell a competitive technology that is also cost effective. The rest of the paper presents average "first approximation" cost per cubic meter based on statistical modeling on recently collected data on costs for different flow rates from equipment manufacturers in North America. We show that there exists a menu of cost effective technologies that might be considered for possible modernization of small water treatment plants.

This paper is structured as follows: Section 1 presents a scheme which classifies water treatment technologies based on the contaminants they remove; Section 2 shows projected costs of four technologies which are ultra violet disinfection (UV), micro filtration–ultra filtration (MF–UF), high rate clarification & filtration (HRC), and ozonation; Section 3 is an analysis of the costs of Advanced Oxidation Processes; Section 4 makes reference to Reverse-Osmosis (RO) and Nano-Filtration (NF) technology for the sake of completeness but these are generally not considered suitable for small water systems as they are expensive. In Section 5 we present examples of costs of actual existing small water treatment systems in Canada. Finally Section 6 is a general summary with concluding remarks. Our major conclusion is that for surface water sources except those sources with high color and/or high turbidity, UV is a competitive and viable treatment technology that should be considered in a menu of suitable technologies. However the actual adoption of a treatment technology depends on many site-specific features (such as location, distance from major cities, and topography) which are best determined by the consulting engineers.

2. Section 1

Suppose we consider a large state-of-the-art water treatment plant and use their costs of water treatment as an initial benchmark. One such treatment plant is the Greater Vancouver Regional District (GVRD) plant that will come on stream soon and will give us a perspective on costs at a large water plant. The source water for this GVRD plant is of high quality and is free of micro-pollutants, largely because of the source water quality. Table 1 gives some information of this system. Due to economies of scale, the GVRD plant has the potential to produce drinking water at CAN $0.40 per cubic meter. However, when the distribution costs are added, it is anticipated that the consumer will pay about $1 per cubic meter. This provides a comparative benchmark of the costs at a large state-of-art water treatment system and shows to what extent the costs of small water systems differ from those at a large system.

Not all systems can produce at the cost and level of drinking water quality that the Vancouver plant is expected to produce. But our survey of new technologies suggests that there are technologies for small systems with similar low average costs per cubic meter. As stated before, in general costs depend on the *number* of contaminants removed, although there may also be other nonlinearities. Below we provide a scheme which would allow us to classify a given water treatment plant by the contaminants removed, based on technology being utilized at the plant. We postulate six classes of water treatment technologies in Table 2.

Class 1 represents the minimum level of treatment which is disinfection by chlorination only. We

Table 1
Description of GVRD state-of-the-art water treatment plant

Parameter	Description
Capital cost	$1 billion
Capacity	900,000 m^3/day
Break-even cost	$0.40/$m^3$
Treatment system	Sand filtration, UV and hypochlorite

Table 2
Proposed water treatment classes

Class	Typical treatment technology	Contaminants removed
Class 1	Chlorination	Water disinfection; removal of most pathogens
Class 2	High rate clarification & filtration	Disinfection plus suspended solid removal
Class 3	Ultra violet	Class 2 plus removal of Protozoa
Class 4	Ozonation	Class 3 plus removal of dissolved organic matter (no DPB[a] precursors)
Class 5	Advanced oxidation process	Class 4 plus the removal of chemicals and other micro pollutants (e.g. pesticides, pharmaceuticals, taste and odor concerns)
Class 6	Reverse osmosis or distillation	Class 5 plus removal of salinity

[a] DPB stands for "disinfection by products."

consider chlorination the minimum disinfection treatment level since all water treatment plants are required to produce water that is free of pathogens. While most ground water-based systems would rely on chlorine only (Class 1), many surface water small water systems will be Class 2, i.e. water that has suspended solids removed and is disinfected. In a Class 3 plant, protozoa will also be removed, possibly with the aid of UV or ozonation. If, in addition, all dissolved organic matter is also removed before chlorination, then that would be water without disinfection by-products (DBP), and we classify such treatment technology as Class 4.

On the other hand Class 5 represents a technology that also removes chemicals, micro-pollutants, DBPs, protozoa and suspended solids in addition to disinfection. In the scheme proposed above, each progressively higher treatment class indicates a greater removal of contaminants. However, this classification scheme is fairly broad in scope, an initial attempt, although other more finely graded classifications are possible. Note that we are classifying *treatment categories or classes, not final water quality.* In this paper we are interested in the main technologies for small systems and what contaminants can be removed from raw water. What emerges from this classification is a comparative cost structure that may be of use to water engineers, planners and decision-makers of small water systems, for water quality that meets regulatory standards.

For each treatment class, we also hypothesize the shape of the cost curves. Average costs per volume of water treated will vary with (a) source water quality, (b) flow rate and (c) target water quality. We expect that for a given type of source water quality, average costs per cubic meter depend on economies of scale. For a *given* source water quality, Fig. 1 below shows the hypothesized (theoretical) average costs as a function of the flow rate for different treatment classes. This graph assumes that contaminants are additively separable and linear.

In reality, that assumption of linearity and additive separability would not hold as some technologies can have an overlap in their functions. For example, technologies which can remove suspended solids (Class 2) can also remove some pathogens (Class 3) and possibly some DBP precursors (Class 4), if used in conjunction with coagulation. Nevertheless it might be useful to assess the *cost differentials* between some of the above mentioned treatment classes, and the extent to which nonlinearities might indicate that it would be better to aim at a higher treatment class that happens to have a lower average costs per cubic meter even if water quality regulations require just disinfection and no additional removal of contaminants. There is also a further nonlinearity already implicit in Fig. 1, namely economies of returns to scale, which suggests that for some smaller communities it might make economic sense to consider a somewhat larger plant scale in the expectation of a future growth in water demand, or consider an amalgamation of two or more small communities supplied by a single but larger treatment plant.

It would be interesting to find the average costs per volume of water of the broad water treatment

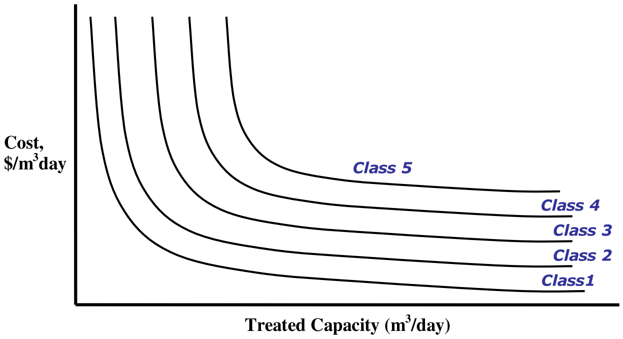

Fig. 1. Hypothetical costs curves and scale of treated drinking water.

classes and find any nonlinearities in costs where the actual average costs curves may not conform to the hypothetical graph in Fig. 1 but in fact exhibit discrete "jumps" indicating the presence of nonlinearities in costs and complementarities in contaminants removed.

3. Section 2: projected costs: ultra violet, micro-filtration–ultra filtration, high rate treatment and clarification, and ozonation

In this section, we present four technologies that may be suitable for small systems: High rate treatment & clarification, UV, micro-filtration ultra-filtration (MF–UF), Advanced Oxidation Processes (based on UV), RO–NF and ozonation. The raw data for costs for different flow rates were obtained from the actual manufacturers (see footnotes for details). For all estimated models, we find average costs per volume of treated water, where the costs are (1) capital costs, amortized (by straight-line depreciation) over a 20 year period, and (2) O&M costs, that include labor, materials and energy costs for given flow rates.

In the case of surface water, UV based technologies would most likely require that source water be pretreated using a filtration or sediment removal process before being disinfected by UV. For communities that are concerned about pesticides and other micropollutants, advanced oxidation processes (AOPs) may be worth considering. However, AOPs may not be practical for small systems but with the implementation of new regulations on drinking water quality in the future, it may be worthwhile for small systems to include UV-oxidation based treatment technologies in their menu of possible technology options. We include AOPs because there are some small communities that are already using AOPs for surface water treatment and also for ground water remediation, even at a small scale.[1]

We briefly describe each technology in Table 3[2] and illustrate the statistically modeled costs associated with each of them thereafter. All the technologies considered here produce municipal standard drinking water, and most assume that the raw source water is surface water which is easily contaminated by animals and/or human activity.

We use the non-linear least squares (NLLS) estimation process since it can capture a wider range of functional forms than the ordinary least squares (OLS) method. Simple linear models may not describe certain data generating processes very well especially if the functional form changes over its domain. For instance, our cost data for UV (see Fig. 2) shows that a much better description of the data can be had if a non-linear approach (solid line) is used instead of a strictly linear one (dashed line). In fact since most of our data followed the same format as in Fig. 2, we used the NLLS method to estimate cost functions for the different classes of technology. The NLLS technique has the added advantage of yielding better estimates when the amount of data is limited.[3]

Table 4 shows the estimated cost functions for the various technologies[4] described above with the functional form $y_i = \beta_1 X_i^{\beta_2} + \varepsilon_i$ where y_i is the average cost per cu. m, defined as capital plus O&M, X_i is the flow rate in cubic meters and ε_i is the error term which satisfies the standard Gaussian assumptions.

Details of the NLLS regressions and model fit statistics are given in the estimations provided in Table 4 above are based on disinfection for the particular technology only and does not take into account the additional cost of residual chlorine for the distribution system, which is required in the US and Canada. We assume that this additional cost would be the same for all the technologies listed above in Table 4 and was therefore left out. In any case for any *actual plant*, there will be many plant-specific costs that the consulting engineers will need to take into account. Therefore the costs given by the cost models should be viewed as the first approximation to costs; costs of specific water treatment plants are likely to vary.

From Table 4 we can observe that both the MF–UF and high rate clarification & filtration (HRC) drinking

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[1] Stockton California remediates its groundwater using Trojan UV Environmental Contamination Treatment, an AOP; their flow rate is 1,100 m^3/day.

[2] A hyperlink to companies which produce each technology is provided for further review.

[3] A reviewer has suggested that if we make the error term multiplicative, then we could estimate the model by simply taking logarithms. That is true, but then we would have to assume that the logarithm of the error term is normally distributed. There is no justification for such an assumption. Here we follow the standard statistical model in which the error term is always additive, representing all omitted variables. The objective is to estimate economies of scale given by the estimated exponent in the nonlinear least squares model. This estimated exponent is the constant elasticity, as is well known.

[4] Data were obtained from John Meunier Inc. (for HRC), Kruger USA (Actifloc), Trojan Technologies (UV), KOCH Membrane (MF–UF), US Filter Memcor (MF–UF) and Mainstream Water Solutions Inc. Data for HRC and MF–UF were in US dollars and were converted to Canadian dollars. However, all data were converted to a base year (2008) in Canadian dollars for proper comparison.

Table 3
Treatment technologies

Technology	Description	Treatment class
High rate treatment & clarification[a]	• Consists of a clarification system (Actiflo) and filtration system (Dusenflo Mixed Bed Filters) • Reduces turbidity, color, suspended solids, algae, taste and odour (T&O), metals and total organic carbon • The resulting filtered water from the Dusenflo gravity filter can contain little or no Giardia and Cryptosporidium cysts • **MINIMUM PLANT SIZE: 473 m^3/day**	Class 2
UV swift[b]	• Utilizes the ability of ultra violet rays to deactivate microorganisms • This system on its own is chemical free and produces no disinfection by-products • However, it can also be used in conjunction with other treatment processes forming a "multi-barrier" approach for treating water for drinking purposes • UV will inactivate bacteria, viruses and protozoa, including Giardia and Cryptosporidium with a dose of 40 mJ/cm^2 • We assume some filtration system to remove sediments (e.g. sand filtration) would be required and is included in the cost • **MINIMUM PLANT SIZE: 200 m^3/day**	Class 3
MF–UF[c]	• Micro filtration and ultra filtration involves separating water from organic and inorganic matter contained in the water by forcing it through a micro porous membrane • Pore sizes in microfiltration membranes are 0.1–10 μm thick while ultra filtration membranes are between 0.001 and 0.1 μm • Microfiltration will remove Giardia and Cryptosporidium cysts, bacteria, and some viruses; however not all viruses can be removed via this process • Microfiltration is also used in sterilization of beverages and pharmaceuticals, clearing of fruit juices, wine and beer, separation of oil-water emulsions and pre-treatment of water for nano filtration and reverse osmosis • Ultra filtration removes all viruses, bacteria and suspended solids between 0.001 and 0.1 μm. Ultra filtration is used in paint treatment, oil-water emulsion separations, the food industry and textile industry • **MINIMUM PLANT SIZE: 379 m^3/day**	Class 3
Ozonation[d]	• Ozonation systems utilize the ability of ozone to inactivate microorganisms through oxidation • The system consists of an ozone pretreatment unit, a BioSand filter and a BioCarbon filter • The roughing filtration system removes suspended solids and coliforms as well as some Cryptosporidium • The BioSand Filter is used to treat parasites, color, cysts, manganese, mercury, iron and turbidity while the BioCarbon Filter treats dissolved organic carbon, tannins, pesticides, iron, bacteria, color and odors • **MINIMUM PLANT SIZE: 11.4 m^3/day**	Class 4

(*Continued*)

Table 3 (*continued*)

Technology	Description	Treatment class
Advanced oxidation (based on UV)	• UV-oxidation process designed to provide disinfection and Taste & Odor treatment; it destroys Geosmin and 2-methylisoborneol • Also removes pharmaceutical, personal care products, pesticides and trace contaminants • System consists of a UV reactor, H_2O_2 dosage and storage system. We assume some filtration system to remove sediments (e.g. sand filtration) would be required and is included in the cost • **MINIMUM PLANT SIZE: 818 m^3/day**	Class 5
RO–NF[e]	• Removes all suspended solids, viruses, bacteria, pathogens and all forms of biological contaminants • Removes mono and multivalent ions, salts and organics • Essentially passes only pure water. Smallest pore size for membranes to date • **MINIMUM PLANT SIZE: 1,893 m^3/day**	Class 6

[a] Produced by Veolia Water Solutions & Technologies in France under subsidiaries John Meunier and Kruger USA.

[b] Produced by Trojanuv Technologies in Canada.

[c] MF and UF information obtained from Koch Mebrane Systems and Lenntech Water Treatment Solutions.

[d] Information for ozonation obtained from Mainstream Water Solutions Inc.

[e] A thorough description can be obtained from Koch Membrane Systems.

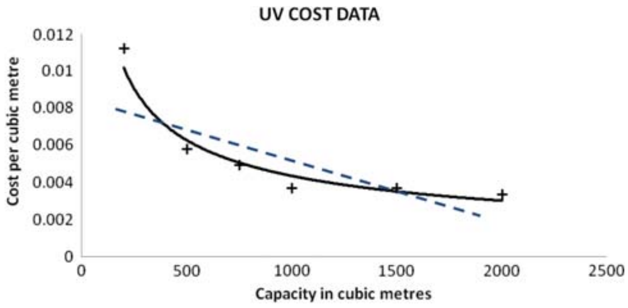

Fig. 2. UV linear vs. nonlinear estimation of cost data.

Table 4
Estimated average cost functions for high rate clarification & filtration (HRC), UV, MF–UF and ozonation in 2008 CDN dollars

Disinfection technology	Average cost function	Predicted cost per cubic meter based on plant with daily capacity		
		100 m^3	200 m^3	500 m^3
HRC	$y = 0.3226x^{-0.2503}$	0.10	0.09	0.07
UV	$y = 0.2653x^{-0.6003}$	0.07	0.06	0.06
MF–UF	$y = 0.4171x^{-0.3048}$	0.10	0.08	0.06
Ozonation	$y = 2.2107x^{-0.381}$	0.38	0.29	0.21

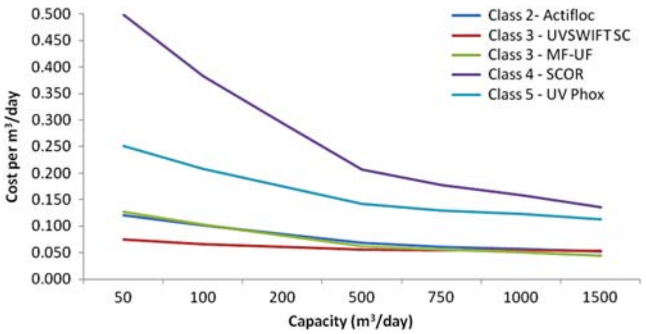

Fig. 3. Estimated cost curves: Class 2 for HRC, Class 3 for UV and MF–UF, Class 4 for ozonation and Class 5 for a UV-based AOP.

water treatment can cost on average 10 cents per cubic meter for a 100 m^3 sizes plant. For surface waters, UV seems to be cheaper than HRC, but direct comparison could be misleading as a lot of location-specific factors need to be taken into account. (Examples of a location-specific factors would be the quality of source water, the presence of color or turbidity, etc.) For UV, some additional costs must be added for suspended solid removal, such as sand filtration, which could add up to 5 cents per cubic meter and has been included in Table 4 and in Fig. 3. Ozonation seems to be the most expensive but of course it can remove more contaminants and goes beyond disinfection. Perhaps this jump in the classes is a *nonlinear feature* and therefore the cost per cubic meter increases by an anomalous amount from Class 3 to Class 4.

Ozone treatment plants[5] are expanding rapidly in small systems across Saskatchewan and Manitoba in Canada, mostly for surface water sources. There are currently about 30 small ozone plants in operation (at the end of 2010). Compared to a UV-based treatment plant, this is more expensive but nevertheless it is proving to be attractive to a number of smaller communities.

4. Section 3: Class 5 treatment technologies

UV-based advanced oxidation process (AOP) is classified as a Class 5 treatment technology in Table 1. Hydrogen peroxide absorbs UV light in order to form free hydroxyl radicals which aid in breaking down contaminants. A combination of UV-photolysis and UV-Oxidation is therefore used in the treatment process. In Table 5 we present the estimated NLLS average cost function for such an AOP.

Details of the NLLS estimate are shown in Appendix A2. We included an additional cost for filtration for surface waters for this AOP of 5 cents per cubic meter in the predicted costs in Table 5. We estimate that Class 5 treatment can cost $0.21 per cubic meter for a small plant which has a daily capacity of 100 m^3. Note that our statistical modeling estimation, based on data supplied by manufacturers, indicates that this Advanced Oxidation Process is cheaper than ozonation and will remove a number of micro-pollutants (see description in Table 3). When plant-specific costs are taken into account our information indicates that a representative plant at a scale of 3,800 cubic meters per day would cost around $0.45 per cubic meter (in 2008 Canadian dollars).[6]

We hasten to add that our cost estimation models yield what we can call “first approximation costs” and what is the most appropriate technology will depend on site-specific (i.e. the particular location) factors which is best left to the consulting engineers to do a thorough cost estimation for specific sites.

5. Section 4: reverse osmosis and nano-filtration (Class 6)

For the sake of completion we should mention Reverse Osmosis and Nano-Fitration, which can also remove salinity, and is therefore classified as Class 6. Dore [6] shows that for a flow rate of 5,000 m^3/day, the cost of producing drinking water was US $0.50 per cubic meter per day in 2005. In a later article Fritzmann et al. [7] put the costs at actual desalination plants to be between US$0.48 and $0.53 cents. Finally in a comprehensive review of the cost of desalination literature, Karagiannis and Soldatos [8] show that the cost of capacities between 500 and 1,000 m^3, RO costs range from US$0.75 cents to $3.93 m^3/day. For capacities less than 1,000 m^3, they find that the costs range from US $2.22 to as much as $19 per m^3 per day. All authors mentioned here recognize the importance of economies of scale in the determination of unit costs.

Table 5
Estimated average cost function for UV-Based AOP in 2008 CDN dollars

Disinfection technology	Average cost function	Predicted cost per cubic meter in CAN $ based on plant with daily capacity in m^3		
		100 m^3	200 m^3	500 m^3
UV-based AOP	$y = 0.7576x^{-0.3394}$	0.21	0.18	0.14

We can also compare the above cost data with the costs of a Point-of-use (POU) Reverse osmosis system. POU costs range from 2.5 to 5 cents per liter or $25 to $50 per cubic meter. These are obviously expensive technologies and possibly not suitable for small water systems. Therefore in this paper we do not pursue these costs any further as our focus is small systems.

6. Section 5: examples of actual costs of a few existing plants

In this section we present costs and flow rates at some existing water treatment plants in select small communities in British Columbia (BC), Canada. As before, the costs are made up was follows: (1) capital costs, amortized over a 20 year period, and (2) O&M costs, that include labor, materials and energy costs for given flow rates. Some of these plants are managed by private corporations as operators and therefore include their profit markup. The cost information was obtained from the managers of these water treatment plants.

Table 6 shows the class and flow rate as well as its associated average operating cost per cubic meter per day. The largest flow rate plant analyzed here produces the least expensive drinking water (compared to other facilities in the same province) at $0.39

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[5] These ozone treatment plants are supplied by Mainstream water solutions Inc. Their brand name is SCOR.

[6] Personal communication from Mr. Morris McCormick, Drinking water treatment plant, City of Cornwall, Ontario.

Table 6
Some examples of existing small water treatment facilities in BC for 2008

Class	Treatment used	Scale (m^3/day)	Operating cost per year ($)	Unit operating cost ($ per m^3/day)
1	Chlorination only	92	41,128	1.23
1	Chlorination only	50	23, 536	1.28
1	Chlorination only	126	40,496	0.88
1	Chlorination only	38	30,202	2.16
1	Chlorination only	778	111,641	0.39
2	Chlorination plus removal of suspended solids	46	46,247	2.72
4	Chlorination plus removal of suspended solids, protozoa and dissolved organic content	640	100,000	0.59

per cubic meter per day. The plant which provides the most costly drinking water also has one of the lowest flow rates.

Using the actual data from these select small systems in BC, we estimate various cost functions for different classes of technology. Note that for Class 1, for some of these communities, the costs reflect (a) profit markup for private sector management and (b) higher transportation costs of hazardous materials such as chlorine and (c) higher transportation costs due to remoteness. These privately managed water systems have costs that include a 100% mark-up on labor costs. We estimated the average cost functions based on the NLLS estimation procedure (see Table 7).

Details of the NLLS estimation are shown in Costs shown above for Class 1 are operating costs for treatment only. Class 1 plants with a daily flow rate of 100 m^3 can produce drinking water at an average cost of $1.00 while the cost is almost quadrupled for a similar sized plant producing Class 4 drinking water on an island off the coast of British Columbia.

Table 7
Examples of estimated average cost functions for BC small systems in 2008 CDN dollars for three capacity levels

Water treatment classification	Average cost function	Predicted cost per cubic meter based on plant with daily capacity		
		100 m^3	200 m^3	500 m^3
Class 1	$y = 19.343x^{-0.6428}$	1.00	0.64	0.36
Class 2	$y = 25.537x^{-0.5998}$	1.61	1.06	0.61
Class 4	$y = 375.873x^{-1.000}$	3.76	1.88	0.75

7. Section 6: summing up and tentative conclusions

We can now show, in Figs. 3 and 4, that with the estimated cost functions, we can reproduce an actual set of cost functions that can then be compared to the hypothetical Fig. 1. Fig. 3 shows the estimated cost curves based on manufacturers rated costs while Fig. 4 shows the estimated cost curves based on a sample of small systems in BC.

Fig. 3 indicates that ozone technology, a Class 4 water treatment, is more expensive than the Class 3 (UV and MF–UF) and Class 2 (HRC) treatment types. Class 3 treatments MF–UF and UV seem to be cheaper than HRC for plants which produce less than 100 m^3 of water per day and all the way up to 500 m^3/day, even though HRC is a Class 2 water treatment process. But in general Fig. 4 suggests that the higher the Class of water treatment the higher the average costs per cubic meter for the sample of small systems in BC.

We observe that the average cost per cubic meter of the statistically estimated equations given above do not conform exactly to the hypothetical Fig. 1 but exhibit the nonlinearities that we expected. Another nonlinearity may be the cost of moving from one technology to another, especially when there has been a long-term commitment to a particular technology.

It is possible that older small systems continue to use higher cost older technologies as there is no incentive to modernize in the public sector. In other words, there are technologies currently available in the market that can provide higher contaminant removal at a much lower cost per cubic meter. Hence, we observe that a technology, which can provide Class 3 and 4 water treatment, shows lower average cost per cubic meter than a small system which is only

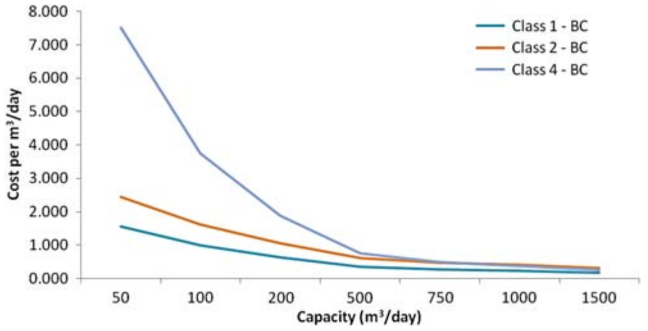

Fig. 4. Estimated cost curves: Classes 1, 2 and 4 for BC small systems.

providing Class 1 and 2 water treatments. Another possible reason is that there are site specific costs which can contribute to the gap in the costs functions between technology and actual existing systems which are in the same class. For example, many of the small systems in BC mentioned above have higher transportation cost due to remoteness and the handling of hazardous materials such as chlorine. However, site specific costs alone cannot account for this very large gap. We observe that some treatment classes at lower flow rates dominate in terms of cost effectiveness. Class 3 MF–UF and UV provide water treatment at a much lower cost per cubic meter than BC small systems Classes 1 and 2 between output flow rates of 50–200 m^3 per day; but at higher flow rates this gap tends to decrease. Finally, the cost per unit for these existing BC small systems is high compared to the rated costs because the systems are privately owned and costs include a mark up for profit.

Before we summarize the conclusions, we need to distinguish between systems that use groundwater as the source and systems that use surface water as the source. Most of this paper is concerned with surface water as the source for water treatment plants.

Based on Figs. 3 and 4 and the results presented in the previous sections, we provide the following tentative conclusions:

(1) The estimated cost curves show that small systems could achieve a higher removal of contaminants at a lower cost than their currently used technology.
(2) A small publicly owned system could get Class 2 and 3 water treatment if they use HRC or MF–UF for about 9–11 cents respectively, provided the flow rate is 100 m^3 per day.
(3) For systems using surface water, UV appears to be the least expensive for small systems at only 7 cents[7] per m^3 for a plant with capacity of 100 m^3 for Class 3, which shows that the competitive advantage remains even when costs of sediment removal are included. We would argue that where primary disinfection is absolutely necessary, UV would compare favorably with chlorine for primary disinfection. Of course in North America a chlorine residual is required by law for the distribution system and perhaps that is why many small systems continue to rely on chlorine as a primary disinfection for surface water systems. The concern over disinfection by products (DBPs) might tip the scale in favour of UV for primary disinfection. But again site-specific considerations need to be taken into account. Furthermore, when the source water is groundwater, which is otherwise free of contaminants, then the only cost is the cost of residual chlorine for the distribution system. In this case chlorine may be cheaper than UV.
(4) If a community is concerned with the removal of micro-pollutants, then a UV based Advanced Oxidation Process would be cheaper than ozonation, provided the flow rate is not too small. (For example, the City of Cornwall in Canada uses AOP for 2 months of the year for taste and odor issues.)
(5) Our results indicate that ozonation is competitive (2008 CDN $), and as such, plants are spreading in Saskatchewan and Manitoba. We estimate that at the beginning of 2011, there are 30 small systems using this technology in the two provinces.
(6) In general, manufacturers' rated costs tend to be lower than actual plant-level average costs as they do not include some plant-specific costs, such as higher labor, energy and transportation costs due to remoteness from large urban areas.
(7) It should be noted that some of the estimations are based on limited data. But there is very little we can do about that. We have tried to do the *best* we can with the available data. Needless to add that the costs estimates cannot be treated for predictive purposes, as all useful predicted costs must also take into account a number of location-specific costs.

Our general conclusion is that while any specific water treatment facility will need to take account of raw source water quality, the *actual* target quality for small systems seems to be to meet only the *minimum regulatory requirements.* Our results show that for surface water, unless the raw water is high in color and in turbidity, a UV-based plant could be economical and cost-effective even when the additional cost of sediment removal is added. This conclusion is especially true for small plants producing less than 100 cubic meters per day. Such a plant could obtain the same or better quality water with UV for less than 8 cents per cubic meter per day. Our finding of the cost effectiveness of UV is in agreement with EPA [1], Gadgil [9] and Parrotta and Bekdash [10].

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[7] Includes 5 cents for sand filtration or sediment removal.

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Appendix 1

Estimation results for Table 4 based on the model: $y_i = \beta_1 X_i^{\beta_2} + \varepsilon_i$ where y_i is the average cost per cubic meter, X_i is the capacity in cubic meters and ε_i is the error term which satisfies the standard Gaussian assumptions

Coefficients	HRC	UV	MF–UF	Ozonation
β_1	0.3226 (0.077)	0.2653 (0.025)	0.4171 (0.060)	2.2107 (0.000)
β_2	−0.2503 (0.027)	−0.6003 (0.000)	−0.3048 (0.003)	−0.381 (0.000)
R^2	0.946	0.975	0.853	0.999
$\overline{R}^2$	0.919	0.968	0.829	0.999
S.E. β_1	0.115	0.076	0.180	0.065
S.E. β_2	0.042	0.048	0.061	0.009
No. of observations	4	6	8	4

p-Values in parentheses.

Appendix 2

Estimation results for Table 5 based on the model: $y_i = \beta_1 X_i^{\beta_2} + \varepsilon_i$ where y_i is the average cost per cubic meter, X_i is the capacity in cubic meters and ε_i is the error term which satisfies the standard Gaussian assumptions

Coefficients	UV-based AOP
β_1	0.7576 (0.4357)
β_2	−0.3394 (0.1397)
R^2	0.759
$\overline{R}^2$	0.638
S.E. β_1	0.784
S.E. β_2	0.142
No. of observations	4

p-Values in parenthesis.

Appendix 3

Estimation results for Table 7 based on the model: $y_i = \beta_1 X_i^{\beta_2} + \varepsilon_i$ where y_i is the average cost per cubic meter, X_i is the capacity in cubic meters and ε_i is the error term which satisfies the standard Gaussian assumptions

Coefficients	Class 1	Class 2	Class 4
β_1	19.343 (0.015)	25.537 (0.494)	375.873 (0.000)
β_2	−0.6428 (0.000)	−0.5998 (0.162)	−1.000 (0.000)
R^2	0.773	0.413	0.999
$\overline{R}^2$	0.765	0.266	0.999
S.E.* β_1	7.456	33.939	0.000
S.E. β_2	0.096	0.351	0.000
No. of observations	29	6	4

*Standard error.

Appendix 4. Sources of data

John Meunier Inc. (2010). *Water and Wastewater treatment: Actiflo® ACP package plants*. Retrieved on October 01, 2011 from: www.johnmeunier.com

Kruger USA (2010). *ACTIFLO® for Drinking Water Treatment*. Retrieved on May 16, 2011 from: http://www.krugerusa.com/en/files/16362.htm

Lenntech (2010). *Micro filtration System (MFS): Membrane Technology*. Retrieved on May 16, 2011 from: http://www.lenntech.com/microfiltration.htm

Mainstream Water Solutions Inc (2010). *Municipal Systems*. Retrieved on May 16, 2011 from: http://www.mainstreamwater.com/topmenu_municipal.html#1

Siemens (2010). *MEMCOR® CP – Ultrafiltration System*. Retrieved on May 13, 2011 from: http://www.water.siemens.com/en/products/membrane_filtration_separation/ultrafiltration_membrane_systems/Pages/memcor_product_cp_membrane_system.aspx

TrojanUV Technologies (2010). *TrojanUVSwiftSC*. Retrieved on May 17, 2011 from: http://www.trojanuv.com/solutions/municipal/drinkingwater/products/trojanuvswiftsc

Koch Membrane (2010). *Municipal Water Ultrafiltration (UF) Systems for Small Communities*. Retrieved on May 16, 2011 from: http://www.kochmembrane.com/mww_prepacked.html

References

[1] US Environmental Protection Agency, Ultraviolet Light Disinfection Technology in Drinking Water Application—An Overview. Office of Ground Water and Drinking Water, Washington, DC, EPA/811-R-96-002, 1996.

[2] Environment Canada, Municipal Water Use, 2004 Statistics, 2004. Available from: http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=ED0E12D7-1

[3] T. Ford, G. Rupp, P. Butterfield, A. Camper (Eds.), Protecting Public Health in Small Water Systems Report of an International Colloquium, May 9–12, 2004, Bozeman, Montana, Montana Water Center, Montana State University, USA, 2005. Available November 1, 2010 from: http://water.montana.edu/colloquium/products/colloquium_report_final.pdf

[4] Journal AWWA, Survey of Water Utility Disinfection Practices, vol. 84, No. 9, dated September 1, 1992.

[5] Disinfection Systems Committee, Committee Report: Disinfection Survey, part 1—Recent changes, Current Practices, and Water Quality, J. AWWA, vol. 100 Iss. 10, October 2008, pp. 76–90.

[6] M.H.I. Dore, Forecasting the economic costs of desalination technology, Desalination, 172 (2005) 207–214, 172.

[7] C. Fritzmann, J. Löwenberg, T. Wintgens, T. Melin, State-of-the-art of reverse osmosis desalination, Desalination, 216 (2007) 1–76.

[8] I.C. Karigiannis, P.G. Sodatos, Water desalination cost literature: review and assessment, Desalination 223 (2008) 448–456.

[9] A. Gadgil, Drinking water in developing countries, Annu. Rev. Energy Environ. 23 (1998) 253–286.

[10] M.J. Parrotta, F. Bekdash, UV disinfection of small groundwater supplies, Am. Water Works Assoc. 90(2) (1998) 71–81.