

Practical Paper

Treatment selection guidelines for particle and NOM removal

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ABSTRACT

Proper selection of appropriate treatment processes for surface water supplies is a function of raw water quality including particles and natural organic matter (NOM). This paper presents an updated foundation for process selection based on routinely measured parameters of particles (turbidity) and organic matter content (UV₂₅₄, color and TOC). The distinction between mineral and non-mineral turbidity is addressed. Processes considered include direct filtration, conventional sedimentation, dissolved air flotation and contact clarification. The results of this paper are based on a survey of currently operating facilities, pilot studies, theory and North American experience. Recommended guidelines for process selection as a function of raw water TOC, color and turbidity are presented. Figures to aid process selection based on source water quality are provided.

Key words | filtration, flotation, NOM, particles, sedimentation, treatment selection

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INTRODUCTION

Achieving finished drinking water quality that meets standards has typically been feasible through conventional treatment of coagulation, flocculation, sedimentation, granular media filtration and disinfection for a wide range of raw water qualities. New standards and goals that focus on reducing disinfection by-products and on reducing exposure to pathogens in drinking water are requiring water utilities to provide improved treatment. Many utilities will be required to upgrade existing processes in order to meet these new requirements and will need to select treatment processes that will provide optimum treatment based on their raw water quality parameters.

Proper selection of appropriate treatment processes for surface water supplies is a function of raw water quality including particles and organic content. Identification of appropriate processes for treatment of a specific water

supply is important to be made early in the planning process as it can save time and reduce project costs. Furthermore, selection of the most appropriate process is critical to achieving consistent high quality finished water. Poor process selection can cause a utility to waste significant capital and operating costs. Therefore, a practical approach to process selection is warranted.

Janssens & Buekens (1993) presented an approach based on raw water turbidity and chlorophyll *a* for preliminary assessment and selection of appropriate processes for removal of particles and algae as shown in Figure 1. Sedimentation, dissolved air flotation and single-stage direct filtration, all widely used treatment processes, were included in their analysis. The less common process of two-stage direct filtration was also included in their assessment. The recommendations they set forth in Figure 1

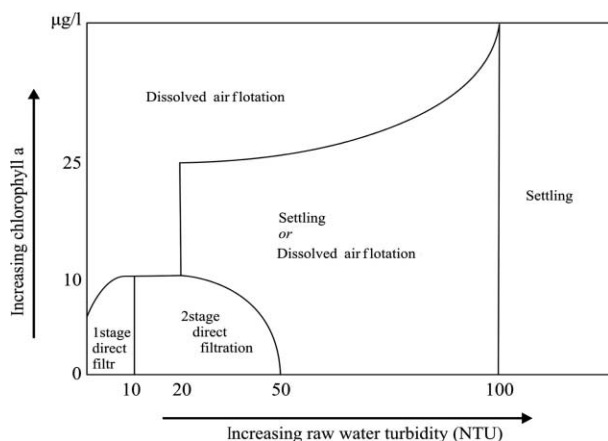


Figure 1 | Floc separation processes: selection diagram (Reprinted from Janssens & Buekens 1993 *J. Water Supply Res. Technol. AQUA* 42(5), 279–288, with permission from the copyright holders, IWA Publishing).

for treatment process selection were based on the authors' experience and their scientific and operational knowledge of drinking water treatment. Janssens & Buekens' paper was an important contribution that aided process selection. However, the figure and their guidelines have some limitations. First, the only measured parameter for natural organic matter (NOM) is chlorophyll *a* for algae. This only accounts for particulate NOM (algae), which for many water supplies is low compared to the dissolved NOM. Also, it is not a routinely measured parameter for most water utilities. Second, they do not distinguish mineral turbidity (clays, silts) from non-mineral turbidity (e.g. algae). Finally, their guidelines do not consider total organic carbon (TOC).

This paper presents an updated foundation for process selection based on more routinely measured parameters of particles (turbidity) and organic matter content (UV_{254} , color and TOC). The distinction between mineral and non-mineral turbidity is addressed. Plant types considered include direct filtration, conventional sedimentation, dissolved air flotation (DAF) and contact clarification. A brief description of each process is provided below.

Direct filtration

Direct filtration does not contain a clarification process but does require coagulant addition to destabilize particles and to remove a small amount of TOC. In some cases,

flocculation is not provided (termed contact or in-line filtration). When flocculation is used, the detention time is typically 10–15 min compared to 30 min for a conventional sedimentation plant. In direct filtration plants particle removal occurs only in the filters, which typically consist of dual media with filter loading rates of 10–15 m/h. In some installations deep bed mono- or dual-media filters (anthracite) or filter adsorbers (e.g. granular activated carbon (GAC)) have been used also at filter rates of 10–20 m/h.

Conventional and high rate sedimentation

A conventional sedimentation plant is one that consists of coagulant addition followed by flocculation, large rectangular or circular sedimentation basins, and rapid media filters. Note that high rate plate and tube sedimentation processes are also considered in this paper. Coagulant is needed to destabilize particles and to provide metal hydroxide floc for adsorption or co-precipitation of NOM. Since new particles are formed by precipitation, chemical coagulation dosing and pH conditions must be carried out such that these particles are destabilized.

Flocculation (slow mixing) is needed to promote particle growth through particle–particle contacts. The goal of flocculation in a conventional treatment plant is to make “settleable” floc, i.e. floc that will readily be removed in a settling basin. The surface loading (or overflow) rate for conventional settling is in the range of 0.5–1.0 m/h, depending on the type of settling process, nature of the raw water turbidity (mineral or non-mineral) and water temperatures. Addition of plates or tubes to sedimentation basins will reduce the footprint of the treatment process by achieving an effective footprint settling rate of 2.5–6.0 m/h. Granular media filtration follows sedimentation to remove any remaining floc particles. Filters typically consist of mono-media (sand) or dual-media (anthracite or GAC and sand) with loading rates of 10–20 m/h.

Dissolved air flotation

A dissolved air flotation plant is similar to a sedimentation plant except flocculated particles are separated from the liquid stream by floating the floc to the water surface.

Coagulant addition and flocculation are still used, but the goal of flocculation in this case is to produce a floc that can be removed by attachment to microscopic air bubbles. Flocculation times for DAF facilities built prior to the mid-1990s were 20–30 min. Since then, it was demonstrated that shorter flocculation times are feasible (for example, Edzwald & Wingler 1990; Valade *et al.* 1996). Full-scale facilities are now often designed with flocculation times of 10 min or less (for example, 5 min for the Croton Water Treatment Plant for New York City (Crossley & Valade 2006; Crossley *et al.* 2007)). Two-stage flocculation is common.

The typical design surface loading rate of the DAF process usually varies between 10–15 m/h—significantly higher than the loading rate on a conventional sedimentation basin and higher than the footprint loading rates for high rate plate and tube sedimentation processes. In addition, high-rate DAF processes have recently been developed at rates of 20–40 m/h (Morris & Hess 2004; Edzwald 2007).

Contact clarification

In this paper, contact clarification is a category used for a variety of processes that includes sludge-blanket clarification, ballasted-sand clarification and contact adsorption clarification. Although each of these specific processes is different from a mechanical perspective, they all work by enhancing particle removal via particle–particle or particle–media contacts.

METHODS

As mentioned above, the selection of the proper treatment plant is a function of raw water quality, finished water goals, and coagulant dose and type.

Raw water quality data and process treatment information were collected from about 400 water treatment plants across the United States and Canada. Primarily, data were obtained directly from contacting water utilities and from the Water:\Stats Water Utility Database (AWWA 1996), an in-depth database of water utility information compiled by the American Water Works Association (AWWA) based on nationwide utility surveys. These

primary sources were supplemented with data obtained from utility databases maintained by equipment manufacturers for utilities that have recently integrated new treatment schemes (e.g. DAF, ballasted-sand, etc.) into their treatment plants, as well as from pilot studies related to upgrading existing facilities with new process schemes.

The Water:\Stats database included data for the following parameters: turbidity, TOC, DOC, color, UV₂₅₄, pH, alkalinity and hardness. Utilities contacted directly were requested to provide average and maximum water quality data for the previous three years for these same parameters. While the additional parameters beyond turbidity represent a more limited set of data compared to turbidity, because fewer utilities make regular measurements of these parameters, they are essential to determining the proper treatment process selection. Additionally, the utilities were queried regarding the type of clarification process utilized, the age of the treatment plant, whether any oxidant is used, the average and maximum coagulant dosages over the three year period, the trophic state of the source water and whether algae are a recurrent problem. These latter data are not included in Water:\Stats.

Data were grouped by plant type into four categories: settling, DAF, direct filtration and contact clarification. As noted above, contact clarification includes sludge-blanket clarification, ballasted-sand clarification and upflow-filtration through plastic media (sometimes called adsorption clarification).

All source water data were evaluated for average and maximum turbidity conditions against average and maximum organic content (i.e. TOC), as well as surrogate organic measurements of UV₂₅₄ and true color. The data in Figures 2 and 3 show that settling plants are used to treat a wide range of water quality—from supplies that are low in turbidity and TOC to those containing high levels of turbidity and/or TOC. Conventional settling was often the only clarification process considered by utilities in the USA prior to the 1990s; hence, most plants built in the USA before 1990 utilize conventional sedimentation. However, the authors of this paper believe that, although sedimentation can be effectively utilized for a wide range of raw water qualities, it is not necessarily the best treatment process for all water qualities. This premise is expanded on below. Plots that focus on direct filtration, DAF and solids

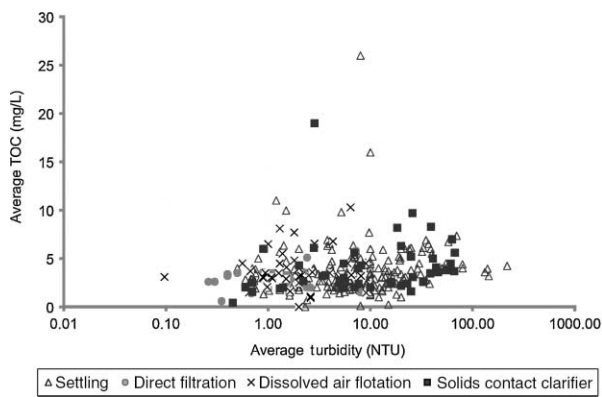


Figure 2 | Survey source water average turbidity and TOC data.

contact clarification were developed. The figures were evaluated to ascertain the limits of the raw water quality parameters for which the different treatment processes have been used in practice. Based on the assumption that sedimentation has been used historically for a wide range of water qualities and potentially misapplied to some water qualities, data for conventional settling were not included in plots provided hereafter in order to provide clarity. It should be noted that some data points for a specific treatment type appeared to be outliers. In these cases, the authors contacted the water utility to verify the effectiveness of the treatment process under the extreme water quality event. For cases when a utility reported the treatment process had difficulty achieving the required finished water quality goals at the desired plant flow rate, the data were removed from the figures.

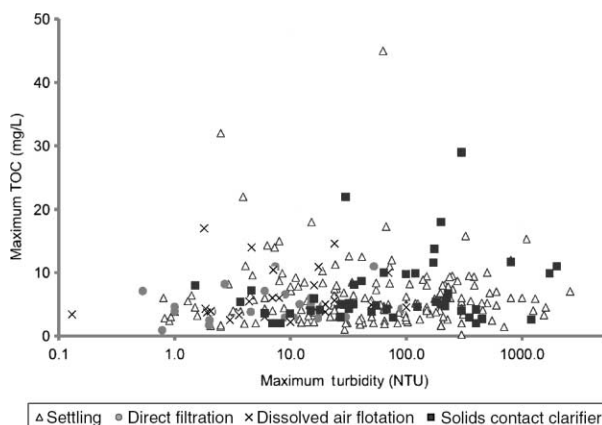


Figure 3 | Survey source water maximum turbidity and TOC data.

RESULTS AND DISCUSSION

For over a hundred years, sedimentation has been used widely as the primary means for clarification of drinking water with a broad range of source water qualities. In the last 40 years, other plant types have been used for particular source water qualities. Table 1 shows the range of ages, as well as the average age, for the treatment plants that are included in this analysis. We were able to obtain the ages of about 25% of the 400 treatment plants; however, we believe the distribution of data in Table 1 is representative and shows clearly that sedimentation has been historically the predominant plant type. Direct filtration and contact clarification plants were introduced on a large scale starting in the 1960s and DAF plants are an even more recent development in the United States and Canada. The first DAF plant in the United States using European-based technology was placed into service in 1993 (Nickols *et al.* 1995). Note that the age of the direct filtration plants in this survey range from 0 to 72 years—aside from one direct filtration plant currently under construction in Canada, no direct filtration plants were built in North America since the advent of DAF in the USA in 1993. Direct filtration plants are limited to treating source waters with very low TOC concentrations (due to disinfection by-product concerns) and they lack a clarification process as an additional barrier to pathogens. The plant currently being constructed in Vancouver, Canada includes UV disinfection as an additional treatment barrier for *Cryptosporidium*. Furthermore, the improved treatment efficiency and lower cost of membrane filtration, particularly for waters with low turbidity and NOM where pretreatment is not required, will likely mean few new direct filtration plants will be constructed in the USA and Canada.

Table 1 | Summary of water treatment plant ages

Plant type	Water treatment plant age		
	Average (yr)	Range (yr)	No. of plants in data
Settling	45	2–107	39
Direct filtration	29	0–72	13
Dissolved air flotation	4	0–14	33
Solids contact clarifiers	35	11–74	7

Note that plants with age of 0 are currently under construction.

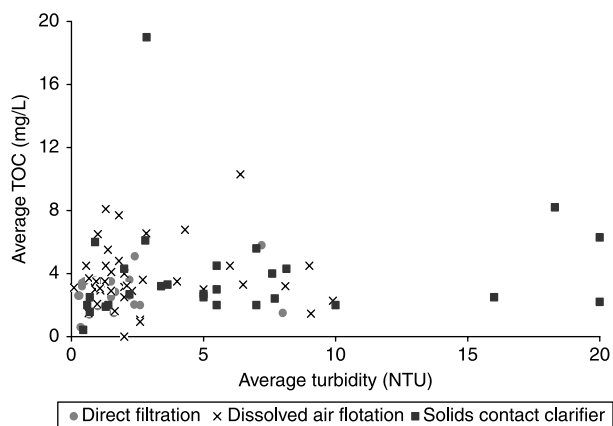


Figure 4 | Survey average source water turbidity and TOC data from Figure 2 excluding settling plant data set.

Turbidity and TOC

The collected data were analyzed in detail for each plant type—direct filtration, conventional clarification, DAF and solids contact clarification. A plot of average source water turbidity versus average TOC for each plant type is presented in Figure 4. The data show that direct filtration plants are used on the highest quality sources—those with average turbidity values generally less than 3 ntu and average TOC levels less than 3.5 mg/L. This makes sense because all of the particle removal in a direct filtration plant occurs in the filters. Higher turbidity or higher TOC levels would result in higher coagulant doses, causing excessive filter headloss development and short filter runs. Higher TOC waters containing even a modest fraction of humic matter demand higher coagulant doses (Pernitsky & Edzwald 2006).

Janssens & Buekens (1993) recommended direct filtration as a feasible treatment process for waters with turbidities less than 10 ntu and 10 $\mu\text{g/L}$ chlorophyll *a*—see Figure 1. Chlorophyll *a* is not addressed in this paper; instead the focus is on TOC (a more readily measured parameter as discussed above). The TOC data in Figure 4 show an upper limit for direct filtration plants of 3.5 mg/L TOC. Pernitsky & Edzwald (2006) suggested direct filtration is feasible for source waters with TOC < 3 mg/L, which is close to this upper limit in the survey data.

Based on the survey data, the Janssens and Buekens' criteria, the Pernitsky and Edzwald criteria, and our own experience, we recommend the following source water

criteria for direct filtration: average turbidity < 5 ntu and average TOC < 3 mg/L.

The early DAF plants in the USA and Canada were built largely to treat high quality source waters. In many cases the supplies were previously unfiltered and DAF was chosen over direct filtration. This biased the survey data since we know from experience around the world that DAF plants have been built to treat waters with a range of raw water qualities, especially when it comes to TOC and non-mineral turbidity (supplies with algae). The survey data show that DAF plants typically have average raw water turbidity levels less than 10 ntu and average TOC levels up to 10 mg/L; however, there is no reason why DAF plants would not be suitable for supplies with higher TOC and non-mineral turbidity levels. High TOC supplies would require higher coagulant doses, but coagulant–NOM flocs have low densities which makes them suitable for removal by DAF. Likewise, non-mineral turbidity also has a low density which would be removed by DAF even at high concentrations.

The data for solids contact clarifiers included in Figure 2 span the < 1–70 ntu turbidity range and have average TOC levels up to 6 mg/L. Note that for clarity in Figures 4–9, the data in the high turbidity range have not been shown.

A plot of maximum turbidity vs. maximum TOC levels is presented in Figure 5. The data show a similar trend to that noted above—direct filtration plants are used to treat the highest quality source water, followed by DAF and then

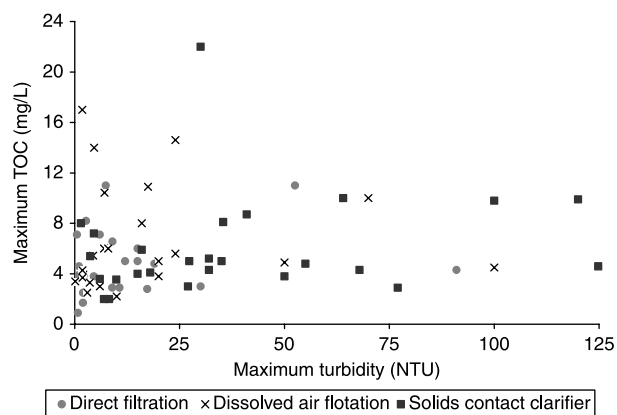


Figure 5 | Survey source water maximum turbidity and TOC data from Figure 3 excluding settling plant data set.

solids contact clarification. The maximum turbidity for a solids contact clarifier was 2,000 ntu (not shown). The maximum turbidity value for DAF was 100 ntu. Although the DAF process can operate at this raw water turbidity level for some time, it would require higher recycle rates for sufficient bubbles to lower floc density or, if typical recycle rates of about 10% are used, then the clarified turbidity would increase, causing higher particle loading on the filters and more frequent backwashing. Although DAF is typically not suited for high mineral turbidity levels, if the turbidity is caused by organic constituents (e.g. algae), then DAF may be a suitable process as mentioned above. Similarly, the maximum turbidity level for direct filtration in this survey was approximately 90 ntu, which is also not sustainable for an extended period of time. Note that maximum turbidity data for settling plants ranged up to 2,700 ntu (not shown in Figure 5, shown in Figure 3).

Turbidity and color

Average source water turbidity versus average color data are plotted in Figure 6. All color data reported herein are true color. Not surprisingly, the color data reveal similar findings to the turbidity and TOC data, with an upper turbidity limit of 3 ntu and 10 ntu for direct filtration and DAF, respectively. Direct filtration plants have been constructed to treat water with average color up to 20 cu and DAF plants to treat water up to 200 cu, but again the authors believe there is no upper limit for DAF plants as the coagulant–NOM flocs would be readily removed through flotation.

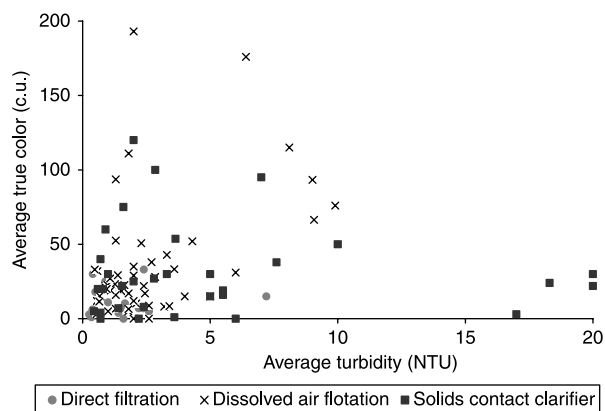


Figure 6 | Survey average source water turbidity and color.

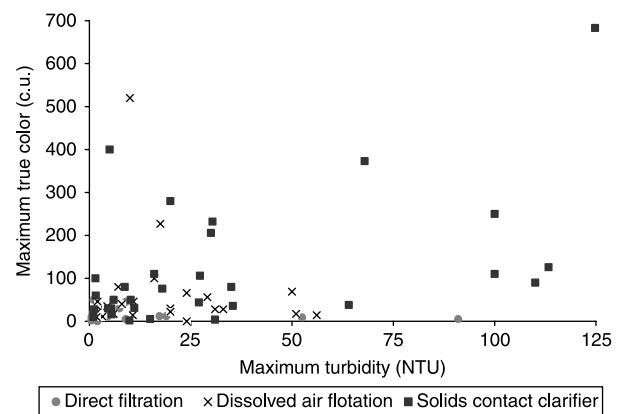


Figure 7 | Survey maximum source water turbidity and color.

Inspection of the data for maximum color (Figure 7) reveals that direct filtration has been used to treat water with color that reach up to 50 cu and DAF has been used to treat waters with color that exceeds 500 cu, although at present for the USA and Canada most source waters with DAF do not exceed 100 cu.

Contact clarifiers have been used to treat a wider range of water with an average color of typically between 20–60 cu and maximum color of nearly 400 cu.

Turbidity and UV_{254}

Average and maximum UV_{254} and turbidity values are plotted in Figures 8 and 9, respectively. The data set is limited as fewer treatment plants reported taking UV_{254} measurements. (Only one contact clarification plant reported UV_{254} measurements and has not been included herein.) However, trends for direct filtration and DAF can

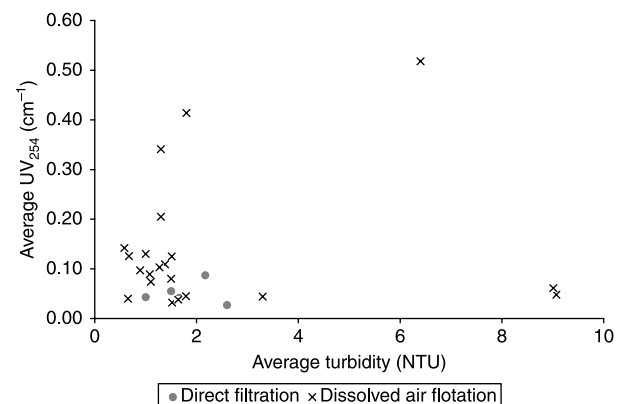


Figure 8 | Survey source water average turbidity and UV_{254} .

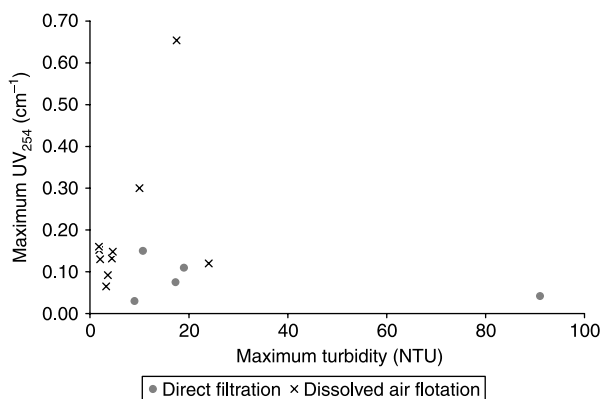


Figure 9 | Survey source water maximum turbidity and UV₂₅₄.

be seen with direct filtration plants having source water with average and maximum UV₂₅₄ less than 0.1 cm⁻¹ and 0.15 cm⁻¹, respectively. Pernitsky & Edzwald (2006) suggested that direct filtration be used only for water with UV₂₅₄ < 0.07 cm⁻¹. DAF plants surveyed have source waters with UV₂₅₄ values up to 0.5 cm⁻¹ and 0.7 cm⁻¹ for average and maximum values, respectively.

RECOMMENDED GUIDELINES

Recommended guidelines for process selection as a function of raw water TOC, color and turbidity are presented in Figures 10 and 11. These guidelines are based on the survey data, the authors' experience, and the Pernitsky & Edzwald (2006) paper for direct filtration. UV₂₅₄ is not included in the figures, but is included in the following text. Presentation and discussion follow:

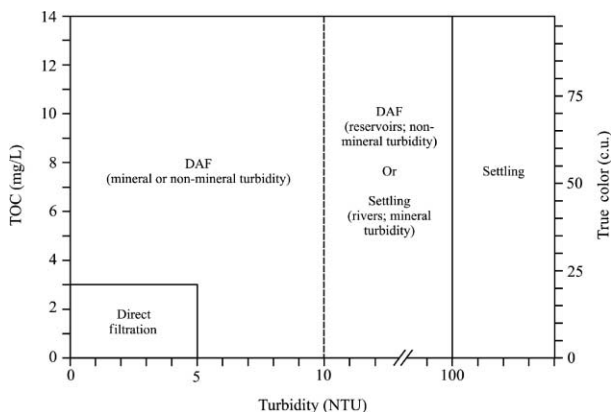


Figure 10 | Process selection diagram based on average water quality.

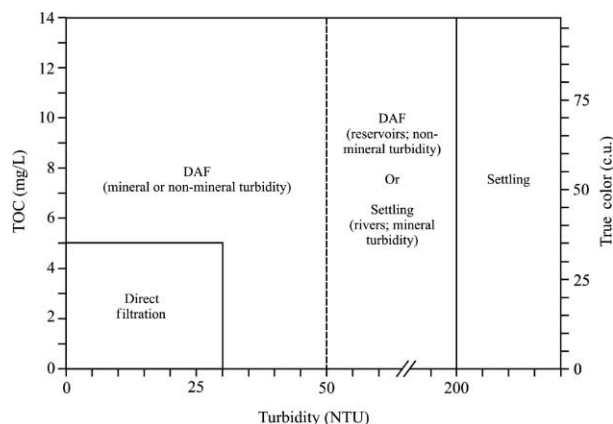


Figure 11 | Process selection diagram based on maximum water quality.

1. Direct filtration plants are most suitable for relatively stable supplies with low turbidity and low organic matter concentrations. High levels of turbidity or natural organic matter (and associated increases in coagulant dose) will overload a direct filtration plant. If direct filtration is determined to be an acceptable process by the users, we suggest that it be limited to supplies with average levels of turbidity < 5 ntu, color < 20 cu, TOC < 3 mg/L and UV₂₅₄ < 0.07 cm⁻¹.
2. Dissolved air flotation plants are more robust than direct filtration plants and can easily handle low to moderate turbidity supplies with high levels of organic matter and color. The authors suggest that DAF plants be limited to supplies with average raw water mineral turbidity levels of 10 ntu or less. Treatment of source waters with higher turbidities is feasible when the turbidity is caused by organic constituents such as algae. There is no upper boundary for TOC or color.
3. The performance of solids contact clarifiers is a function of both raw water quality and the specific type of clarifiers. In general, solids contact clarifiers perform well over a wider turbidity range than direct filtration and DAF. They may be particularly well suited to supplies with a variable source water quality (e.g. low average turbidity and organics, with high maximum turbidity). Some solids contact clarifiers can be problematic on supplies with rapidly changing temperature or when rapid changes in plant flow are required.

4. Conventional settling plants can handle the highest raw water turbidity levels. They are most suited for supplies with average raw water turbidities greater than 10 ntu. Where conventional settling is used on supplies with low turbidity and low TOC, an increase in metal salt coagulant dose is sometimes needed to make enough floc for the clarification process to be effective. When polyelectrolytes or low metal salt coagulant doses are used in a conventional plant, the process tends to perform in a direct filtration mode.

CONCLUSIONS

The paper by Janssens & Buekens (1993) provided treatment plant selection guidelines with respect to raw water quality but was limited to raw water turbidity and chlorophyll *a*. In this paper we extended the evaluation of raw water quality to include mineral and non-mineral turbidity and various measures of organic matter such as TOC, true color and UV₂₅₄. Proper selection of treatment processes based on raw water quality characteristics including turbidity and NOM is important. The recommended guidelines presented in this paper provide a rational way for selecting appropriate treatment processes based on raw water turbidity and NOM parameters such as color, TOC and UV₂₅₄. Our recommended guidelines are summarized in Figures 10 and 11. Conclusions for the selection of treatment plant type based on the guidelines follow.

- Direct filtration is recommended for high quality waters with average raw water turbidities less than 5 ntu and maximum turbidities that do not exceed 30 ntu. Average raw water organic content should not exceed 3 mg/L of TOC or 20 cu of color and maximum raw water organic content of 5 mg/L of TOC or 35 cu of color. However, direct filtration may be further limited to waters with even lower organic content if water age in the distribution system leads to high levels of disinfection by-products, thereby requiring a process that will effectively remove higher levels of organic matter.
- DAF is recommended for relatively high quality waters with average raw water turbidities below 10 ntu from river sources (i.e. mineral turbidity) or 100 ntu from reservoir sources (i.e. non-mineral turbidity), with no

upper limit of organic content. Maximum turbidities can range up to 50 ntu (mineral sources) and 200 ntu (non-mineral sources).

- Solids contact clarifiers are recommended for water qualities having significant variations between average and maximum turbidities.
- Conventional settling can be used to treat a wide range of raw water qualities, but are recommended for waters with maximum turbidities for mineral and non-mineral sources of greater than 50 and 200 ntu, respectively.

ACKNOWLEDGEMENTS

The authors would like to express their deep appreciation to all of the personnel at the water utilities who graciously provided information for this project and to the equipment manufacturers—Infilco Degremont, Inc., ITT WWW Leopold and Parkson Corporation—who provided data, as well as contacts at many of the water utilities. Special thanks are extended to Mr Donald Brailey for the initial idea for this paper, Mr Ian Crossley for his advice and assistance in developing this paper, Ms Eileen Feldman for her efforts supporting the writing effort and to Ms Anni Luck for her assistance in gathering the data and compiling it for analysis.

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First received 23 December 2008; accepted in revised form 26 June 2009