SIMULATION OF COMPLIANCE CHOICES FOR THE DISINFECTION BY-PRODUCTS REGULATORY IMPACT ANALYSIS

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INTRODUCTION

The United States Environmental Protection Agency (USEPA) is in the process of developing regulations designed to limit the concentrations of disinfectants and their by-products in United States drinking water systems. The feasibility of complying with such limits is affected by other regulations, such as the Surface Water Treatment Rule (SWTR), which specifies minimum levels of disinfection to protect against human exposure from pathogens. Also, despite there being microbiological standards in place, different limits for DBPs may significantly affect changes in exposure from pathogens. In developing regulations for disinfection by-products (DBPs), USEPA wants to ensure that drinking water utilities can effectively provide treatment that controls concentrations of both DBPs and pathogenic microorganisms.

As described in a companion paper (Cromwell et. al., 1992), the objective of regulatory analysis is to determine the potential impacts of implementing different regulatory options. The objective of this paper is to describe one aspect of this analysis, the methods used to estimate the following:

- The extent to which utilities might need to change from present treatment practices to other treatment practices in order to meet different regulatory options under consideration;
- The national occurrence of DBP concentrations (currently only for trihalomethanes and haloacetic acids) after the treatment changes are implemented; and
- The national occurrence of pathogens (currently only for Giardia cysts) after treatment changes are implemented.

Trihalomethanes (THMs) and haloacetic acids (HAAs) are targeted because they are among the DBPs identified to date of greatest health concern and models are available that

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predict their formation. Giardia cysts are targeted because: 1) more data are available on their occurrence in source waters than other pathogens; 2) they are much more resistant to disinfection than most other waterborne pathogens; 3) changes in treatment to control for DBPs, assuming that systems must still meet the minimal requirements of the SWTR, are likely to result in more significant changes in exposure from Giardia than from other waterborne pathogens identified to date and 4) dose response data are available for estimating risk from exposure. A companion paper (Grubbs, et. al., 1992) describes in greater detail the rationale and some of the shortcomings in selecting Giardia as the target organism.

This paper presents a revised version of a similar modeling approach and analysis (Gelderloos, et. al., 1991).

MODELING CONCEPT

A Monte Carlo simulation model is being used by USEPA to support the regulatory impact analysis of the disinfection and disinfection by-products regulations. An overview of the simulation model is shown in Figure 1 and discussed in the following paragraphs. This figure focuses on the Malcolm Pirnie/USEPA WTP model (Harrington, et. al., 1991a) which is used to predict the extent of treatment changes needed by utilities to meet the regulation based on a prediction of the occurrence of DBP and Giardia concentrations after the treatment changes are implemented.

Treatment Model Input

As shown in Figure 1, there are three general inputs to the treatment model: 1) process characteristics, 2) raw water quality and chemical dosages for each plant, and 3) treatment constraints. Each of these items is discussed in the following paragraphs.

The overall modelling approach assumes that there are five basic types of treatment practiced in the United States at the present time. The five treatment categories are assumed to be the following:

Surface Waters

- Coagulation/filtration systems;
- Precipitative softening systems; and
- Unfiltered systems (including those that will be required to filter under the SWTR).

Groundwaters

- Unfiltered systems; and
- Precipitative softening systems.

This paper focuses on the approach used for the category of surface water coagulation/filtration. This category represents 103,000,000 people served by systems greater than 10,000 people and 12,000,000 people served by systems less than 10,000 people (AWWA, 1991). (The four remaining categories, depending upon the availability of data, may be analyzed under a similar conceptual approach). The assumed process characteristics for this category are described in the subsequent "Modeling Approach" section.

For the raw water quality and treatment data, the Monte Carlo simulation model uses assumed statistical distributions based on data from existing plants in this category (Letkiewicz et. al., 1992). From these distributions, 100 input data sets were generated, with each set representing a single, hypothetical water treatment plant and its associated water source. For this effort, it is assumed that this large number of these hypothetical water treatment plants and their water sources is considered to be representative of the distribution of water sources and treatment practices in use throughout the United States.

The treatment constraints for this category are designed to simulate the requirements of various regulations, such as the SWTR and the Lead and Copper Rule. The taste and odor constraint helps to define the treatment practices within the plant. Each of these constraints is described in the subsequent "Modeling Approach" section.

WTP Treatment Model and Compliance Sorting Routine

The 100 hypothetical treatment plants are individually evaluated through the treatment model to predict plant effluent and distributed water quality and to determine whether a system meets the treatment constraints and DBP MCLs. The modules contained within the WTP model are briefly described in the "Modeling Approach" section, while a complete description is provided in the WTP User's Manual (USEPA, 1992).

The approach assumes that all treatment plants initially use chlorine as the only disinfectant. A review of existing disinfection practices within this category shows that a known percentage of systems use disinfectants other than chlorine. The majority of such plants have switched from chlorine to alternate disinfectants presumably because of source water quality that compromises compliance with the current THM Rule. Because the data from all the plants within this category are combined to produce input distributions, the model can be evaluated for its accuracy to predict the number of plants which require alternate disinfectants or other treatment modifications to meet the current THM Rule.

The predicted water quality of the 100 plants is evaluated through a "compliance sorting routine". This routine sorts the treatment model output according to alternative DBP MCLs. If a system does not meet the constraints established by the SWTR or the MCL of interest, the system implements the lowest cost modification necessary to meet the constraints. If the new treatment method is not sufficient to achieve compliance with the treatment constraints or the DBP MCL of interest, the next lowest cost modification is added to the treatment plant. This process is repeated for each system until it complies with the treatment constraints and the DBP MCL of interest.

Order of Least Cost Alternatives

For coagulation/filtration plants using chlorine as the only disinfectant, the approach assumes the following order of alternatives, from the lowest cost alternative to the highest cost alternative:

- Eliminate pre-chlorination, if practiced;
- Install ammonia feed system to provide chloramines as secondary disinfectant;
- Increase coagulant dose to improve DBP precursor removal;
- Switch to ozone/chloramines disinfection strategy; and
- Add GAC or membranes.

The implementation of a chlorine/chloramine or an ozone/chloramine disinfection strategy may be effective for complying with both the SWTR and TTHM limits. However, these alternative disinfection strategies may not be appropriate for other DBPs. Therefore, under some possible regulatory scenarios, the implementation of either of these two disinfection alternatives may not be possible. Therefore, the impacts of alternative DBP MCLs were evaluated under two different compliance approaches as shown in Figure 2. One compliance approach assumes that alternative disinfection strategies are available while the other compliance approach assumes that alternative disinfection strategies are not available. Analysis of these two scenarios also allows for national cost comparisons to be made between: 1) use of alternate disinfectants, versus 2) sole use of precursor removal strategies, to achieve different regulatory targets. Such cost analysis is discussed in a companion paper (Cromwell et. al., 1992).

Interaction Between the Treatment Model and Compliance Sorting Routine

If a treatment plant in this coagulation/filtration category used pre-chlorination and could not meet the appropriate constraints, the treatment plant would first eliminate pre-chlorination (if practiced). If this change were sufficient to meet the appropriate constraints, no other modifications would be necessary. If this change were not sufficient to meet the appropriate constraints, the treatment plant would eliminate pre-chlorination but maintain primary disinfection with chlorine following filtration, and install chloramines for secondary disinfection. However, if chloramines were not adequate as an alternative to meet the MCL, the treatment plant would eliminate pre-chlorination and increase its alum dose.

If the MCL of interest is a TTHM limit of 50 $\mu g/L$, the treatment model and sorting routine would first evaluate each system under initial conditions. As the necessary treatment modifications are applied to each system to comply with the treatment constraints and the TTHM limit of 50 $\mu g/L$, the sorting routine produces distributions of calculated DBP concentrations and Giardia concentrations. Therefore, the distribution of water quality for the 50 $\mu g/L$ limit may contain results from systems that do not require any treatment modifications to systems which require the most extensive treatment modifications.

Risk and Cost Models

The distributions of water quality for alternative DBP MCLs and the extent of treatment modifications are applied to the appropriate models. The cancer risk model and national cost model are described by Cromwell et. al., (1992) and the Giardia risk model is described by Grubbs et. al. (1992).

BASIS FOR TREATMENT IMPROVEMENT ASSUMPTIONS

The following paragraphs briefly describe the basis for modeling each of the treatment improvements.

Eliminate Pre-Chlorination: This step involves the removal of raw water chlorine feed system for those systems practicing pre-chlorination. Any disinfection credit achieved by the system in the sedimentation basin prior to this step is maintained by increasing the size of the contact basin following filtration.

Increase Alum Dose: This step involves increasing the input alum dose by 40 mg/L.

Addition of GAC: GAC contactors with 30-minute empty bed contact time and 6-month regeneration frequency are added to the model system following filtration. In addition, the addition of post-chlorine was relocated to a point after the GAC.

Use of Chloramines: Chloramines were formed by adding ammonia at a chlorine residual to ammonia ratio of 4:1 after primary disinfection with chlorine in the contact basin. This ratio was used to reduce the amount of excess ammonia entering the distribution system to reduce the potential for growth of nitrifying bacteria. This ratio was also used to reduce the formation of dichloramine and trichloramine which lead to taste and odor complaints. For the use of monochloramine as a secondary disinfectant, the required chloramine concentration was calculated to meet the following constraints:

- Achieve a chloramine residual of 1.0 mg/L at the maximum residence time in the distribution system to control the growth of nitrifying bacteria in the distribution system; and

- Maintain a chloramine residual less than 3.0 mg/L at the first customer to avoid concern from possible health effects (USEPA is considering proposing an MCLG of 3 mg/L for chloramines [Orme, 1992]).

Ozone/Chloramine: In this strategy, ozone replaces chlorine as the primary disinfectant. The location of primary disinfection is between sedimentation and filtration. The purpose of providing filtration after ozonation is to augment biological removal of assimilable organic carbon (AOC) within the filters. The model, however, does not assume any reduction in chlorine demand or TOC by biological removal through filtration. Also, chlorine demand and TTHM formation is based on TOC concentrations following sedimentation, which is a conservative assumption for this analysis. An ozone dose of 1 mg O_3/mg TOC is assumed to meet CT requirements and the ozone demand of the natural organic material (NOM) remaining after sedimentation. At this time, it is assumed that ozone does not affect THM formation.

The secondary disinfectant for this strategy is monochloramine. Prior to the addition of ammonia, however, a short period of free chlorine contact (one minute at average flow) is provided following filtration for added protection against bacteria sloughing from the biologically active filters.

MODELING APPROACH

A schematic of the baseline model treatment plant is shown in Figure 3. The treatment process consists of a rapid mix, flocculation and sedimentation basin, followed by filtration and a contact basin. A storage basin is provided after the contact basin; however, the residence time of this basin is incorporated into the distribution system residence time. Alum is added prior to the rapid mix basin. Although some of the systems in the coagulation/filtration category use iron salts or other coagulants, the percentage is small (approximately 12 percent). For the purpose of this analysis, the approach assumed that the NOM removal performance of ferric coagulants is similar to alum. Based on a recent survey, 82 percent of systems used a disinfectant prior to filtration (AWWA, 1991; Letkiewicz et. al., 1992;). The survey did not distinguish the precise point of prechlorination, and in the absence of such data, the prechlorination point was assumed to precede the rapid mix.

Caustic is also added before the rapid mix basin if the sedimentation basin pH is predicted to be below 5.5. This pH represents the lower bound used to develop the TOC removal equation and also helps to control residual aluminum. Post-chlorine is added before filtration and the dose is determined by the model (see "Calculation of Chlorine Dose and Contact Basin Size" below). Lime addition, if applicable, is also before filtration to minimize post-precipitation problems in the contact basin. Finally, caustic is added after the contact basin for corrosion control in the distribution system. The caustic dose is a function of the raw water hardness (discussed in "Corrosion Constraints", below).

Figure 4 presents a list of input raw water quality parameters and treatment data used in the model. Letkiewicz et. al., (1992) discusses the approach used to simulate the statistical distributions for these parameters. From these distributions, 100 sets of input data were generated with each data set representing a unique treatment plant. One distribution absent from this list but needed for the model is the pre-chlorine dose. Therefore, for those systems using pre-chlorine, the dose was set by the model to achieve a 0.2 mg/L residual at the end of the sedimentation basin.

The WTP treatment model is used to predict the total trihalomethane (TTHM) and total haloacetic acid (THAA) formation, inactivation ratios and disinfectant residuals associated with each hypothetical treatment plant. The following paragraphs provide an overview of the primary equations used in the model.

Formation of TTHMs is calculated in accordance with equations presented by Harrington, et. al. (1991b), and formation of individual THMs is calculated in accordance with equations presented by Chowdhury and Amy (1991). These equations predict the dynamic behavior of the THM concentrations through the treatment plant and distribution system based on water quality characteristics, such as TOC, UV-254, temperature, pH and bromide. THM formation in the presence of chloramines is assumed to be 20 percent of the rate of THM formation in the presence of chlorine. This 20 percent factor is based on an estimate developed by Amy et. al. (1990).

Formation of individual HAAs is calculated in accordance with equations developed by Haas (Patania, 1991). These equations predict the concentration of individual HAAs (currently limited to mono-, di-, and tri- chloroacteic acid; and mono- and di- bromoacetic acid) at a given location in the treatment plant or distribution system. The HAA equations are based on statistical correlations between THMs and HAAs and therefore, do not account for the cumulative effect of changing water quality parameters throughout the treatment plant and the distribution system.

Dynamic HAA equations are currently being developed by the D/DBP Technical Advisory Workgroup (TAW) but these equations were not used in this analysis. Additional work will consider incorporation of these equations into this analysis. For the analysis presented in this paper, the equations developed by Haas (Patania, 1991) are used.

Finally, chlorine decay is calculated in accordance with the equations presented by Dharmarajah, et. al. (1991). Chloramine decay equations were developed by Malcolm Pirnie, Inc. based on data developed by Dharmarajah, et. al., (1991). A description of these equations is provided in the WTP User's Manual (USEPA, 1992).

To model the compliance behavior of plants following the SWTR, Lead Rule, and Coliform Rule, but prior to the DBP Rule, certain constraints must be applied to the model. The constraints attempt to restrict the operation of treatment systems to a region of feasible operation with respect to the regulations. The following paragraphs list the constraints applied to the model.

SWTR Constraints

The SWTR constraints include disinfection requirements through the treatment plant and in the distribution system. The modeling approach assumes that plants will operate with a safety factor to ensure continuous compliance during abnormal conditions.

For disinfection through the treatment plant with chlorine, the chlorine dose is calculated to achieve at least 20 percent greater inactivation than required in the SWTR. In other words, the disinfection requirements are based on a sum of $CT_{calc}/CT_{req'd}$ of 1.2 at minimum temperature and peak hourly flow. Use of the ratio, $CT_{calc}/CT_{req'd}$, also referred to as the inactivation ratio, is described elsewhere (USEPA, 1991). CT_{calc} is the calculated CT determined from t_{10} values and chlorine residuals from each treatment process in the plant. $CT_{req'd}$ is the required CT value for a specific temperature, pH, and chlorine residual to achieve a specified level of inactivation. $CT_{Req'd}$ can be estimated from the following equation (Clark and Regli, 1991):

$$CT_{req'd} = 0.36(Cl_2)^{0.15}(pH)^{2.69}(T)^{-0.15}\left[-\log_{10}\left(\frac{N}{N_0}\right)\right] \quad (1)$$

where Cl_2 is the chlorine residual at the end of the contact time (measured as free chlorine in mg/L), T is the temperature of the disinfected water in degrees Centigrade throughout the contact time (within 0 to 5 degrees), pH is the pH throughout the contact time (within the pH range of 6 to 9), N is the concentration of Giardia cysts remaining after the contact time and N_0 is the concentration of Giardia cysts prior to the contact time. For temperatures above 5 degrees the predicted required CT is multiplied by one-half for every 10 degree increase. For example, the equation can be used to estimate the required CT at 15 degrees by applying the equation at 5 degree and multiplying the result by one-half. The temperature used in this equation is the minimum temperature because lower temperatures require greater disinfection. Equation 1 calculates values of $CT_{req'd}$ that are within 10 percent of the values listed by USEPA (1991). Therefore, the safety factor used may actually be less than 20 percent but is at least greater than 10 percent.

The required log inactivation is given as follows:

$$log\ inactivation = -\log_{10}\left(\frac{N}{N_0}\right) \quad (2)$$

Because the model assumes a 2.5-log removal by filtration, the required level of inactivation for a plant with a 3-log removal/inactivation requirement would be 0.5 times the safety factor of 1.2, or 0.6. Therefore, the total log removal/inactivation would be 3.1 (2.5 plus 0.6). For an "Enhanced SWTR", the log removal/inactivation requirement depends on the level of contamination in the source water. (The Enhanced SWTR is described in the "Results of Enhanced SWTR Scenario" in a subsequent section). Because the amount of removal by filtration is assumed constant, the level of required inactivation depends on the Enhanced SWTR guidelines.

For disinfection in the distribution system, the chlorine dose is calculated to achieve at least a 0.2 mg/L residual at a point representing the maximum residence time in the distribution system. This constraint is beyond the minimum requirement of the SWTR that at least a detectable residual (which may be total residual) be maintained at 95 percent of the sampling points in the distribution system. The higher residual concentration is assumed necessary for maintaining detectable residuals throughout most of the distribution system and for ensuring high probability of compliance with the Coliform Rule.

Taste and Odor Constraint

To minimize chlorinous tastes and odors, the chlorine dose is calculated to maintain a chlorine residual entering the distribution system of less than 2.0 mg/L (Krasner, et. al., 1984). Although some treatment plants currently maintain higher chlorine residuals without any taste and odor concerns, this conservative constraint is used for the purposes of this modeling approach. Because some systems will not be able to meet the minimum residual requirement at the end of the distribution system without exceeding the taste and odor constraint, the modeling effort requires these systems to modify their treatment to meet the constraint.

DBP Constraints

Without making any significant changes to treatment practices, a utility can observe significant variability in running annual average TTHM concentrations. As shown in Figure 5, the peak running annual average TTHM concentration can be 20 percent higher than the mean running annual average TTHM concentration. For this analysis, the other DBPs are assumed to exhibit similar variability. To account for this variability, the percentage of systems meeting a specific DBP MCL was based on maintaining a mean running annual average DBP concentration of 80 percent of the specific MCL. For example, systems with a TTHM limit of 50 μg/L would be required to maintain a simulated TTHM average concentration of less than 40 μg/L (80 percent of 50 μg/L). A similar approach was used for each total THM and total HAA limit under consideration.

Corrosion Constraints for Lead Rule

Corrosion control is modeled in all systems by maintaining at least a minimum pH level based on raw water total hardness values. Other expected corrosion control measures, such as use of orthophosphate inhibitors, are assumed to not significantly affect DBP levels and are thus not assigned any other constraint condition. For those systems with raw water total hardness values greater than 100 mg/L, the distribution system pH was adjusted upward, if necessary, to achieve at least 7.6. A higher pH is not considered for these systems out of concern for precipitation of calcium carbonate. For those systems with raw water total hardness values less than 100 mg/L, the distribution system pH was adjusted upward, if necessary, to at least 8.0. These minimum pH values are simplifying assumptions to address the lead and copper rule limits promulgated in May 1991.

Distribution System Chlorine Demand

The treatment model was developed to predict chlorine decay in the distribution system based on the amount of chlorine demand present at the plant effluent. Currently, there are no models for predicting chlorine decay specifically based upon demand exerted by the distribution system characteristics (e.g., corrosion by-products and biofilms). In an attempt to account for the distribution system chlorine demand, the parameters contributing to chlorine demand (TOC and UV-254) were increased by an arbitrary percentage upon entering the distribution system. The 20 percent increase in TOC and UV-254 assumed in this analysis caused an additional 10 percent of systems to exceed the chlorine constraints listed above (chlorine residual and taste and odor constraints).

The 20 percent assumed increase in TOC and UV-254 was modeled to only affect the chlorine decay prediction and not the predictions of DBP formation. Chlorine and chloramine decay models for the distribution system are needed to more accurately model this aspect of the analysis, but none are currently available.

Calculation of Chlorine Dose and Contact Basin Size

To simulate the post-chlorine dosages and contact basin sizes required for compliance with the SWTR and other regulations, the model was programmed to calculate the most efficient combination of design variables for a given system to meet all the constraints listed above. This most efficient combination is expected to occur with the smallest contact basin size and maximum feasible chlorine dose, because the contact basin is expected to control cost (Harrington, 1991a). To illustrate the process used, the following example considers a conventional surface water treatment plant using a chlorine/chlorine disinfection strategy and assumed raw water qualities.

The first constraints considered for each system are a distribution system pH for maintaining corrosion control (see discussion above) and the SWTR requirement that a detectable residual be present throughout the distribution system. This latter constraint was simulated by requiring a minimum chlorine residual of 0.2 mg/L at the maximum distribution residence time. Figure 6 shows the minimum chlorine dose required for a range of contact times in the chlorine contact basin at average flow. This system could meet these two constraints by operating at any point above the curve for this constraint.

The next constraint considered for each system is the SWTR requirement to achieve primary disinfection, or CT. For each system, the objective was to achieve an inactivation ratio of 1.2 at minimum temperature and at peak hourly flow. The chlorine dose required to achieve this constraint is also plotted in Figure 6 (contact times at peak hour flow were converted to average flow and a log removal of 2.5 is assumed through filtration). Again, the selection of any chlorine dose above this curve allows the system to meet the CT constraint.

Finally, for each system, the amount of chlorine entering the distribution system is limited to 2.0 mg/L in an attempt to limit taste and odor concerns in the distribution system. The chlorine dose versus contact time curve established for this constraint is shown in Figure 6. In this case, any operation below this curve allows compliance with this constraint. *However, the only region where this system meets all four constraints is shaded in the figure and labeled as the "Region of Feasible Operation".*

The model was programmed to determine the furthest left point in the region of feasible operation. This point corresponds to the minimum feasible contact basin size. The DBP concentrations at the average distribution system and Giardia concentrations at the plant effluent were then computed with this contact basin size and chlorine dose.

RESULTS OF SWTR SCENARIO

This section discusses the results of the analysis using the SWTR requirement of a minimum 3-log removal/inactivation through the treatment plant. The treatment model described in this paper generated the following results:

- Percentage of systems meeting the SWTR and existing THM Rule;

- Percentages of systems requiring treatment modifications to meet the SWTR and DBP goals;

- Mean TTHM and THAA concentrations at the average customer for selected DBP goals; and

- Mean Giardia concentrations at the first customer for selected DBP goals.

Figures 7 through 10 illustrate the treatment model output under the SWTR minimum 3-log requirement. Figures 7 and 8 indicate predicted compliance choices for systems to meet the selected TTHM goals of 25, 50, 75, and 100 $\mu g/L$ under two different compliance approaches: One approach assumes alternate disinfectants are not available (Figure 7), and the other approach assumes alternate disinfectants are available (Figure 8). A similar evaluation of the THAAs using goals of 10, 20, 30, 40, 50, and 60 $\mu g/L$ is presented in Figures 9 and 10 for the two different compliance approaches. Note that in some cases, especially when alternate disinfectants are not available as a treatment option, some systems are unable to meet the target MCL even with the use of GAC. The percentage of such systems, which would need to seek a variance, is indicated in the small upper left hand figure below the table in Figures 7, 9, and 10.

Systems Meeting SWTR and Existing TTHM Rule

The compliance percentages associated with the TTHM MCL of 100 $\mu g/L$, shown in Figures 7 and 8, represent the predicted behavior of treatment systems in this category to meet the SWTR, taste and odor, and corrosion control constraints and the existing THM Rule. These results provide an estimate of the effects of the SWTR and Lead Rule on existing compliance behavior. The results show that 61 percent of systems would meet all the constraints using chlorine as the only disinfectant and without any further modifications to existing treatment conditions. An additional 21 percent of the systems would meet all the constraints after the elimination of pre-chlorination. For the remaining 18 percent of systems which do not meet all the constraints, 11 percent would need to increase the alum dose and 7 percent would need to add GAC, if alternate disinfectants are not available. If alternate disinfectants are available, the remaining 18 percent would meet all the constraints after switching to monochloramine as the secondary disinfectant.

According to the Water Industry Database (AWWA, 1991), 63 percent of the coagulation/filtration systems treating surface waters currently use chlorine as the only disinfectant, 25 percent use chloramines and 12 percent use ozone or chlorine dioxide. In other words, 37 percent use alternate disinfectants. Assuming that all the systems currently using alternate disinfectants are doing so to meet the existing THM Rule, the modeling results appear to under predict the number of plants that would require alternate disinfectants (18 percent). It is important to note, however, that the elimination of pre-chlorination was considered prior to the use of alternate disinfectants in the modeling analysis. In practice, some plants which pre-chlorinate or prechloraminate have switched to chloramines to meet the 100 $\mu g/L$ MCL and continue to disinfect prior to filtration. It is possible that some of these plants may have been able to meet the MCL by eliminating pre-chlorination, without the use of chloramines. Additionally, the assumption that alternate disinfectants are being solely used to meet the existing MCL may not be valid for every system. There may be other reasons, besides THM control, which cause some plants to use alternate disinfectants. Therefore, the results for a TTHM MCL of 100 $\mu g/L$ may simulate treatment behavior more closely than indicated by the initial comparison of predicted and actual alternative disinfection practices.

Compliance Percentages for Alternative MCLs

As expected, the percentage of systems able to meet alternative TTHM and THAA MCLs decrease as the MCL decreases. Consequently, the percentage of systems requiring treatment modifications increase as the MCL decreases. The compliance percentages presented in Figures 7 through 10 provide a basis for estimating the upgrade costs for each selected DBP MCL.

DBP Occurrence Analysis

Further examination of the modeled systems which are unable to meet all the constraints at a TTHM MCL of 100 $\mu g/L$ shows that these systems exceed either the THM MCL or the chlorine constraints in the distribution system (i.e., residual constraint of 0.2 mg/L at the end of the system or the taste and odor constraint of 2.0 mg/L at the first customer). For example, of the 39 (100 minus 61) systems which are unable to meet all the constraints with "No Further Treatment", 21 do not meet the chlorine constraints and the remaining 18 meet the chlorine constraints, but exceed the 100 $\mu g/L$ MCL. Because of the method used by the model to calculate post-chlorine dose and contact basin size, if the chlorine constraints cannot be met for a particular system, the model does not predict DBP formation for the system.

The result of the above approach is that the mean DBP concentrations at given treatment steps are calculated using only those systems which meet the chlorine constraints. Therefore, the mean TTHM and THAA concentrations of 55 and 24 $\mu g/L$, respectively, for the systems requiring no further treatment are calculated from the 79 (100 minus 21) systems which meet the chlorine constraints. The 21 systems which do not meet the chlorine constraints generally have poorer source water quality (higher TOC and/or UV-254) and would most likely produce THM levels above the mean concentrations. As treatment modifications are applied, these systems meet the chlorine constraints and are included in the mean calculations. Therefore, evaluating the changes in the mean concentrations at different treatment steps is somewhat misleading.

The primary focus of comparison should be on the mean concentrations after all the treatment modifications have been applied or after all the systems meet a selected DBP goal. The comparison of the mean values associated with different DBP MCLs gives an indication of the average reduced DBP exposure from different DBP regulatory scenarios. For each DBP MCL evaluated in Figures 7 to 10, these mean concentrations are highlighted.

Microbial Occurrence Analysis

For both disinfection alternatives, the model predicts higher mean Giardia concentrations as the MCL for a given DBP is lowered, and as treatment modifications to improve precursor removal are added. (This trend is shown graphically on the small figures included on Figures 7 through 10). The reason for this trend is a result of how the model sets the post-chlorine dose and contact basin size. As described in the "Modeling Approach" section of this paper, the post-chlorine dose is set to meet three chlorine constraints: distribution system residual, CT and taste and odor. The distribution system residual and CT constraints define the minimum dose, while the taste and odor constraint defines the maximum dose. In cases where the minimum dose is defined by the distribution system residual constraint (high chlorine demand waters), the dose required to meet the CT constraint is exceeded, resulting in inactivation that exceeds the minimum CT. Therefore, a higher inactivation is calculated for waters with higher chlorine demand. As processes to increase precursor removal are added, the chlorine demand decreases, and the minimum dose is more often defined by the CT, not the distribution system residual. Therefore, as the chlorine demand of the water decreases, lower CT values are calculated (approaching the minimum requirement), thus increasing the predicted risk of microbial infection. Note that this analysis does not quantify any benefit of disinfecting a cleaner water (with possible improved inactivation efficiency) as a result of removing TOC or chlorine demand.

Although in practice every plant which increases precursor removal may not reduce its chlorine dose to meet the minimum disinfection requirement, this analysis shows the possible outcome of plants faced with lower DBP MCLs if they were only required to minimally meet the SWTR. It is important to note that in practice many systems, some of which have very high concentrations of Giardia cysts in the source water, currently have much higher levels of disinfection than minimally required under the SWTR (LeChevalier et. al., 1991). At higher DBP MCLs many of these systems would be able to maintain such disinfection practice and still meet the DBP MCL. However, at lower DBP MCLs, many of these systems, in the absence of regulatory constraints to prevent otherwise, might adopt low cost DBP control technologies (e.g., shifting the point of chlorination or switching to chloramines) and decrease the level of Giardia inactivation provided to the extent of only minimally meeting the SWTR. Thus, greater changes in Giardia concentrations could be expected than are predicted between the high versus low target MCL scenarios in this modeling analysis. Also, the rates of these types of risk tradeoffs could be more significant to the populations for individual systems than to the populations considered for the aggregate of all systems. This issue is further discussed in the companion paper by Cromwell et. al., (1992). The Enhanced SWTR, discussed in the next section, eliminates the possibility of increased risk from Giardia that might result from increasingly stringent DBP MCLs.

RESULTS OF ENHANCED SWTR SCENARIO

Although the SWTR currently requires a minimum 3-log removal/inactivation of Giardia to meet CT requirements, USEPA recommended that utilities achieve greater inactivations depending on the degree of contamination within the source water (USEPA, 1991). This paper refers to this guidance as the "Enhanced SWTR". According to these guidelines, a system should consider providing a 3-, 4-, or 5-log removal/inactivation based on the source water Giardia concentrations to ensure that the rate of infection from Giardia is less than 1/10,000 people per year beyond the first customer. The input distribution of Giardia to the model, however, contains values exceeding the maximum concentrations listed in the Guidance Manual. Therefore, an extension of the log removal/inactivation requirements was made to include 6- and 7-logs. The following table summarizes the SWTR guidelines including the extension of those guidelines for the purpose of this analysis:

Daily Average Giardia Cyst Concentration/100 L (Geometric Mean)[1]	Recommended Giardia Removal/Inactivation
≤ 1	3-log
1-10	4-log
10-100	5-log
100-1,000	6-log
1,000-10,000	7-log

The only difference between the modeling approach for the Enhanced SWTR and the SWTR scenario presented previously is the amount of disinfection required in the plant depending on the raw water Giardia concentrations. All other constraints are identical to those described in the SWTR scenario. First order kinetics are assumed in extrapolating the CT values necessary to achieve all levels of inactivation.

Figures 11 through 14 present a summary of the treatment model output under the Enhanced SWTR requirements. Figures 11 and 12 reflect the model predictions for the selected TTHM goals of 25, 50, 75, and 100 μg/L under two different compliance approaches: One approach assumes alternate disinfectants are not available (Figure 11), and the other approach assumes alternate disinfectants are available (Figure 12). A similar evaluation of the THAAs using goals of 10, 20, 30, 40, 50, and 60 μg/L is presented in Figures 13 and 14 for the two different compliance approaches.

Compliance Percentages for Alternative MCLs

The compliance percentages for the Enhanced SWTR scenario exhibit the same trends as the SWTR scenario: The compliance percentages decrease as the MCLs decrease and the percentage of systems requiring treatment modifications increase as the MCLs decrease. Of greater significance, however, is that the predicted percentages do not dramatically decrease, if at all, when the Enhanced SWTR requirements are imposed. A comparison of the compliance percentages predicted from the SWTR scenario and Enhanced SWTR scenario for systems requiring no further treatment is shown in the table below for selected TTHM MCLs:

Percentage of Simulated Treatment Plants Complying with TTHM MCL				
	TTHM MCL (μg/L)			
	100	75	50	25
SWTR Scenario	61	49	33	17
Enhanced SWTR Scenario	61	49	32	14

[1] - EPA guidelines (USEPA, 1991) are based on a geometric mean but in this modeling analysis the arithmetic mean is used for purposes of conducting statistical analysis.

These comparable results are observed throughout most of the Enhanced SWTR scenario. The reason for this result is that the additional contact time within the plant required by the Enhanced SWTR (which is assumed can be added, if needed, to meet the inactivation target) does not significantly change the predicted concentration of TTHMs or THAAs at the average customer. Because the average residence time in the distribution system averages about 1.6 days, the additional one to three hours in the plant does not significantly increase the TTHM or THAA concentration at the average customer *when using chlorine as the only disinfectant.*

Differences in compliance percentages for the two regulatory scenarios only appears to occur slightly at the lower DBP MCLs. At lower MCLs, the additional CT required for chlorination to achieve the inactivation requirements of an enhanced SWTR, appears to be significant enough to prevent some systems from meeting the DBP MCL, particularly at an MCL of 25 μg/L.

These results imply that requiring greater inactivation of Giardia for more highly contaminated source waters may not significantly impact the costs of compliance. The approach assumes that the cost for increased contact basin size will be included in the compliance costs, but will not significantly influence the total cost. However, if systems do not have space available to increase contact basin size, which many apparently do not, other options might then be required (e.g., a stronger disinfectant such as ozone which could significantly increase treatment costs).

DBP and Microbial Occurrence Analysis

For reasons discussed above, the increased contact times required for the Enhanced SWTR do not significantly increase the TTHM or THAA concentrations at the average customer. A comparison of the mean TTHM concentrations for the SWTR scenario and the Enhanced SWTR scenario after all the treatment modifications have been added is shown in the table below:

Mean TTHM Concentration After Treatment Modification				
	TTHM MCL (μg/L)			
	100	75	50	25
SWTR Scenario	40	33	25	15
Enhanced SWTR Scenario	41	36	26	15

Similar results are obtained for THAAs. These results imply that requiring greater inactivation of Giardia for more highly contaminated source waters will not significantly increase the predicted cancer risk if systems as a whole are required to also meet a specific DBP MCL.

Because an enhanced SWTR would require higher levels of disinfection for more highly contaminated source waters, all waters would be treated to approximately the same range of effluent Giardia levels. As a result, systems with contaminated sources would not be allowed to sacrifice their disinfection practices to meet the DBP goals. Currently, however, simple-to-use practical analytical methods for quantifying the occurrence of Giardia cysts in source waters (and ideally also distinguishing which are viable and infectious to humans) are not available for determining the appropriate level of treatment. Another issue is whether or not Giardia would be the appropriate target organism (rather than, e.g., Cryptosporidium) under such a regulatory framework.

CONCLUSIONS

This paper presents the general approach used to simulate compliance behavior for one treatment category. A similar approach may be used for one or more of the remaining treatment categories depending upon the data that become available.

The predictive equations used in the model are continually being reviewed and developed. The accuracy of the predictive equations depends on the ability of these equations to accurately predict treatment performance over a wide range of treatment conditions. Although the treatment model may not accurately predict treatment performance on a plant-by-plant basis, the model is designed to simulate the general treatment performance for large numbers of systems. The results presented in this paper show how modeling can be used to predict compliance behavior.

Perhaps the most important modeling result, if the predictions are valid, is that the universe of systems that use surface water and which practice coagulation and filtration could use almost the same decision tree of treatment technologies (but with differences in the level of disinfection) to meet the existing SWTR and stringent DBP MCLs as they could to meet an enhanced SWTR and stringent DBP MCLs. This implies that the costs for complying with these two different regulatory scenarios would not be significantly different even though much greater microbial protection could be provided under an enhanced SWTR, if such a rule could be implemented.

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Figure 1

Overview of Treatment Model

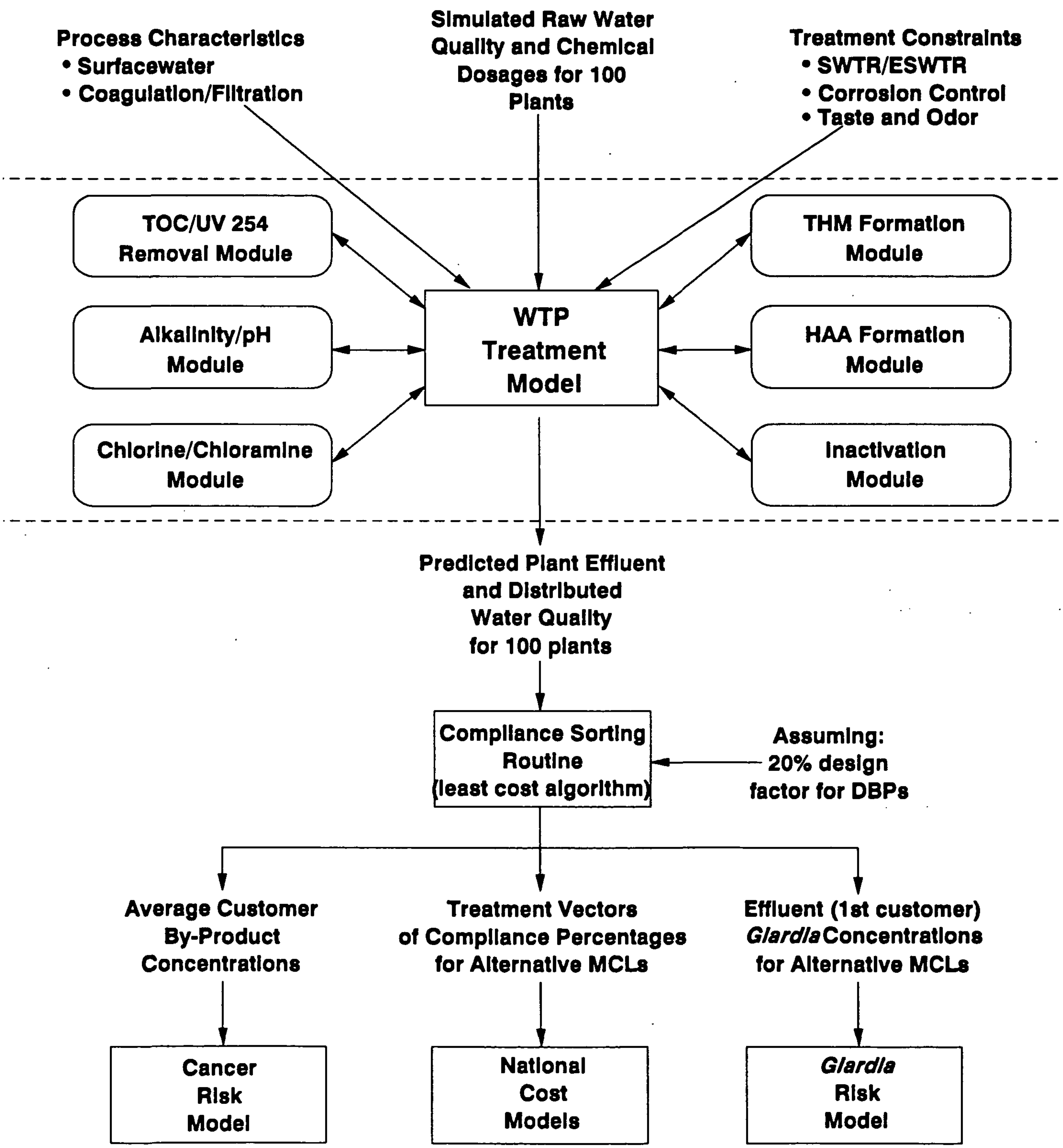


Figure 2

Modeled Compliance Approach

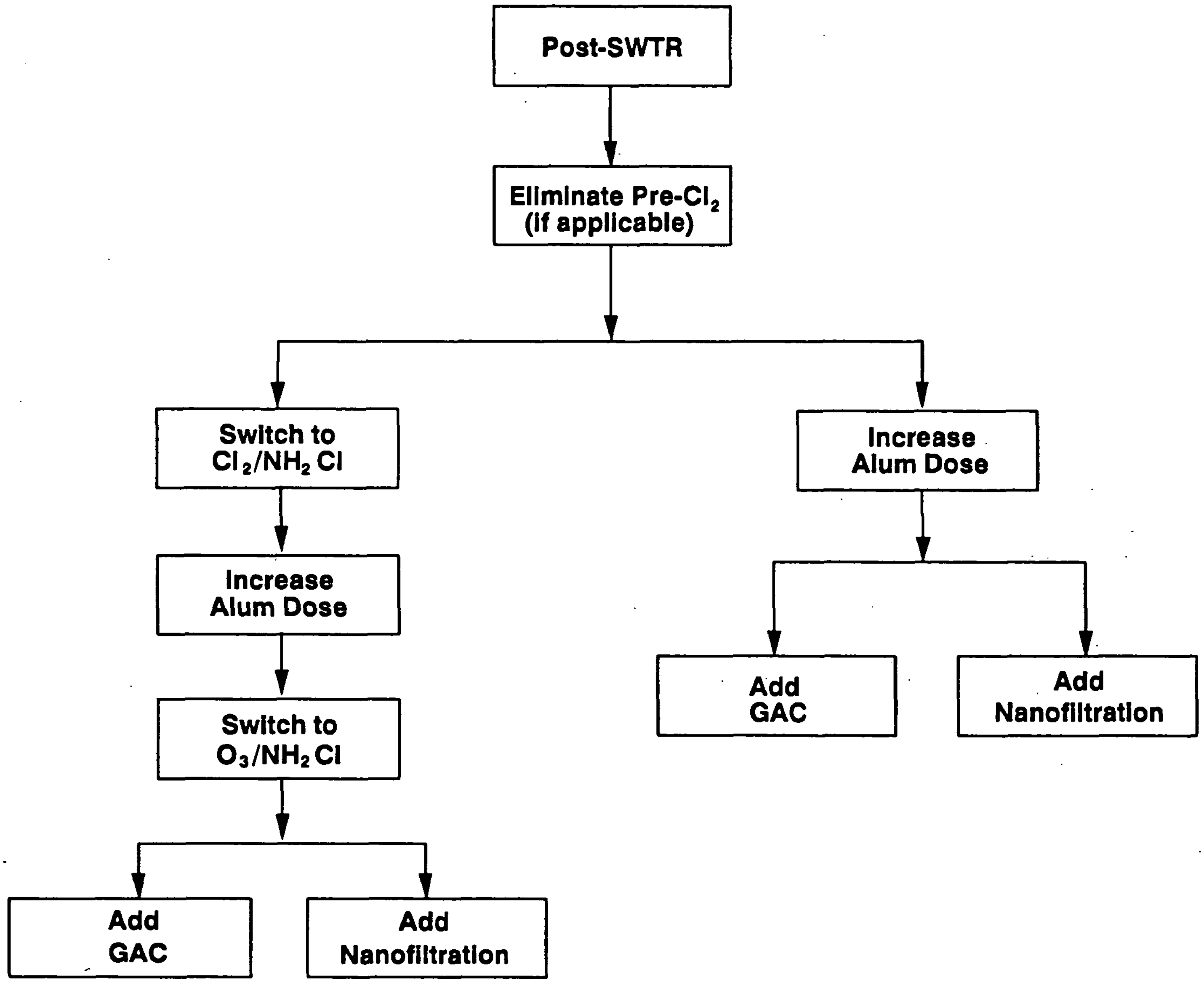
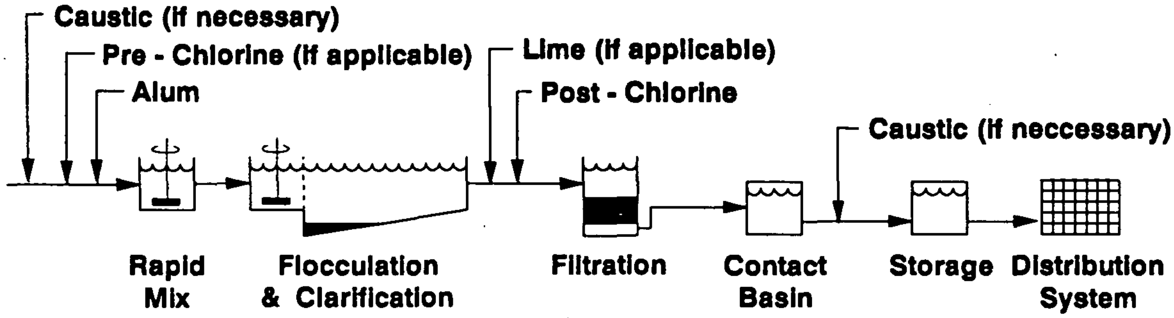


Figure 3

Model Treatment Plant



MODEL ASSUMPTIONS

SEDIMENTATION BASIN

- Theoretical Residence Time = 4.5 hours (Including Flocculation and Rapid Mix)
- t(10) at Peak Hourly Flow + Theoretical Residence Time at Average Flow = 0.70
- t(mean) at Average Flow + Theoretical Residence Time at Average Flow = 0.90
- Sedimentation basin pH restricted to values greater than 5.5 since TOC removal equation only valid down to this pH. Caustic added to increase raw water pH, if necessary.

FILTRATION

- Theoretical Residence Time = 15 minutes
- 2.5 log removal of Giardia credit
- t(10) at Peak Hourly Flow + Theoretical Residence Time at Average Flow = 0.50
- t(mean) at Average Flow + Theoretical Residence Time at Average Flow = 1.0

CONTACT BASIN

- t(10) at Peak Hourly Flow + Theoretical Residence Time at Average Flow = 0.70
- t(mean) at Average Flow + Theoretical Residence Time at Average Flow = 0.90
- Residence time calculated by model

DISTRIBUTION SYSTEM

- Maximum Residence Time = 2 x (Average Residence Time)
- Level of pH adjustment by caustic based on total hardness

Figure 4

Model Inputs to Treatment Plant

Raw Water Quality

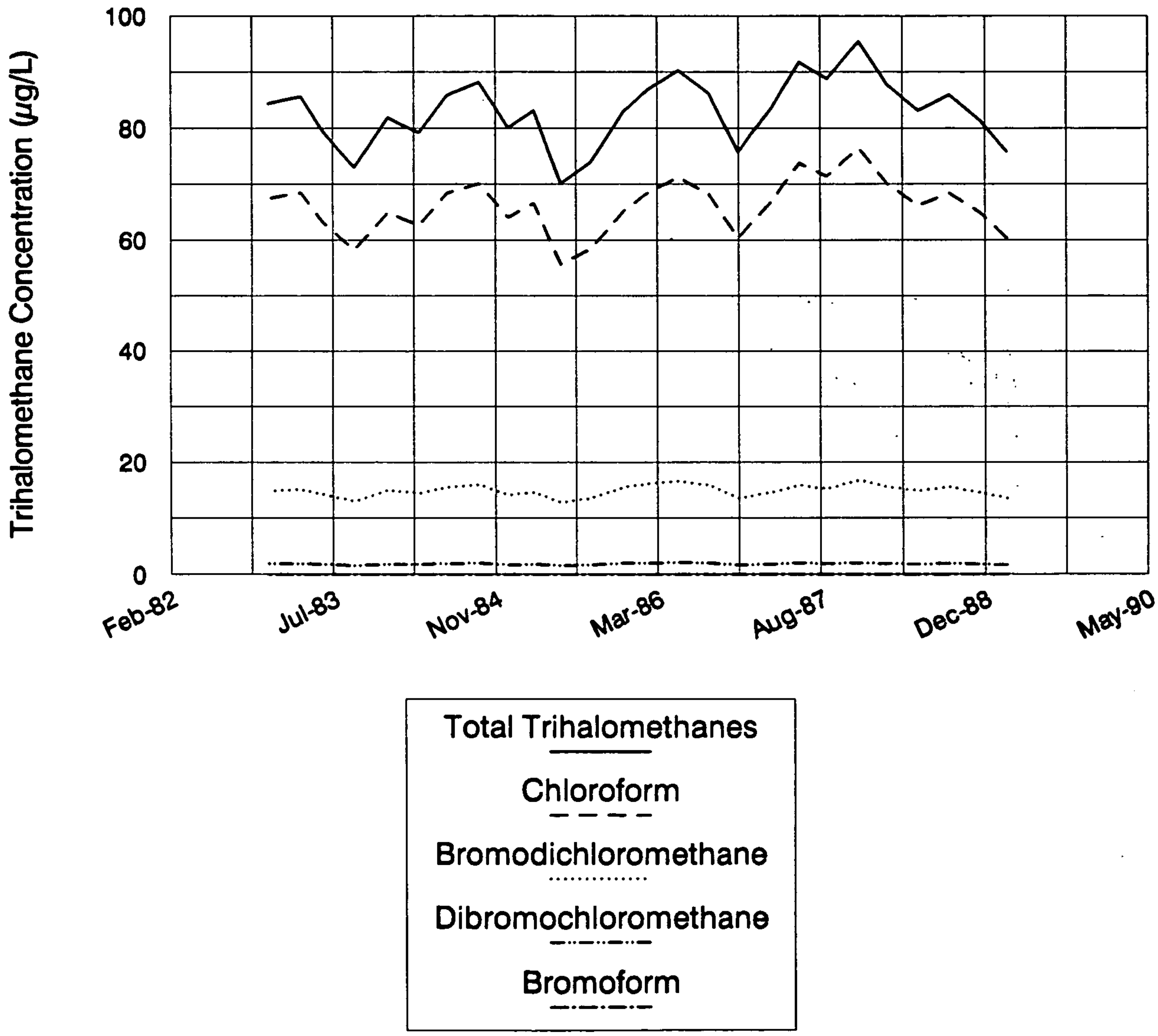
- TOC
- UV-254
- Bromide
- pH
- Alkalinity
- Total Hardness
- Calcium Hardness
- Turbidity
- Average Temperature
- Minimum Temperature
- Ammonia
- Giardia

Treatment Data

- Alum Dose
- Lime Dose
- Average Daily Flow
- Pre-Cl_2 (Y or N)
- Average Distribution Residence Time

Figure 5

Running Annual Average Trihalomethanes



Contact Basin Design

CHLORINE/CHLORINE DISINFECTION STRATEGY

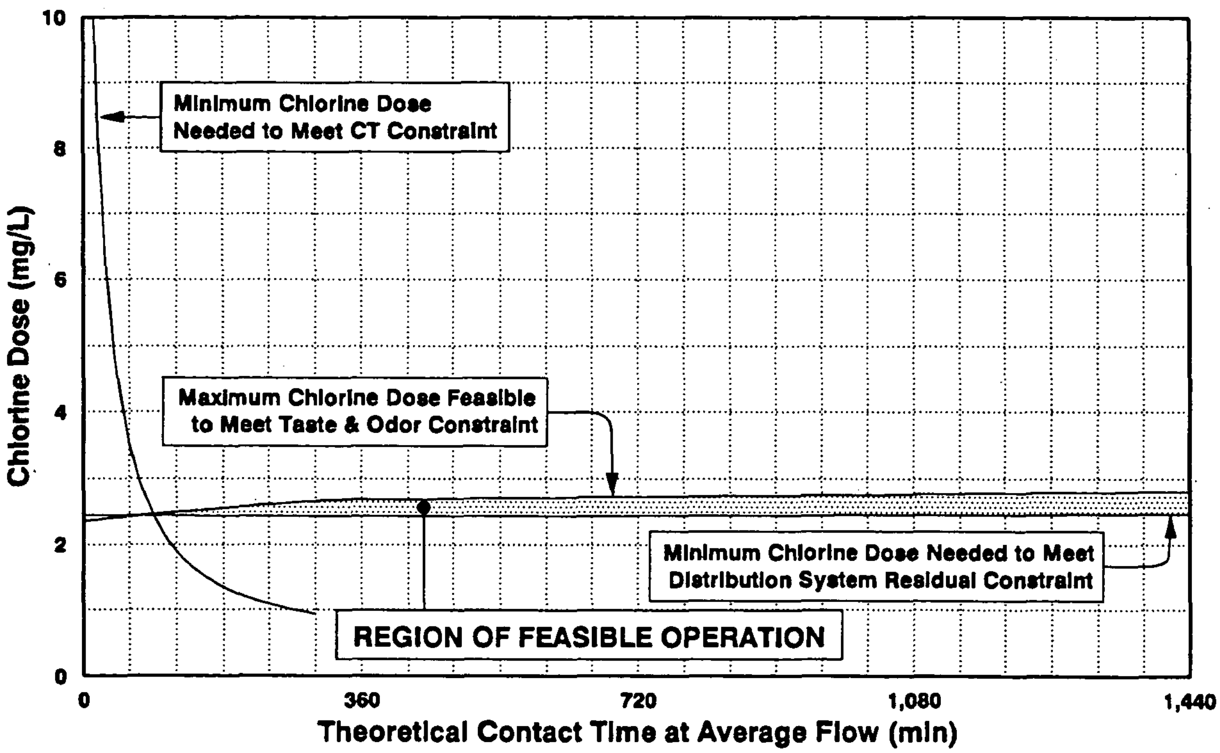


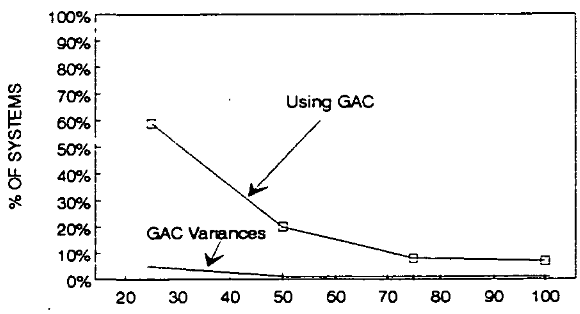
Figure 7

MODEL OUTPUT (surface w/o softening): SWTR W/O ALTERNATIVE DISINFECTION

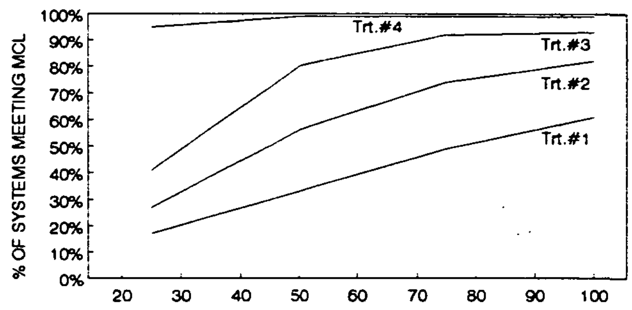
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

TTHM MCL[1] (μg/l)	Treatment Code	% of Sys. Ending[2]	Cumulative Percentage of Systems < MCL[3]	Mean Concentrations of By-Products at Avg.Cus. (μg/l)[4]		Mean Concentration of Giardia at First Customer[4] (cysts/100 L)
				TTHMs	THAAs	
100	1	61	61	55	24	0.04
100	2	21	82	42	20	0.08
100	3	11	93	40	20	0.09
100	**4**	**7**	**99**	**39**	**19**	**0.12**
75	1	49	49	55	24	0.04
75	2	25	74	39	19	0.09
75	3	18	92	35	18	0.10
75	**4**	**8**	**99**	**34**	**17**	**0.13**
50	1	33	33	55	24	0.04
50	2	23	56	37	18	0.11
50	3	24	80	29	15	0.13
50	**4**	**20**	**99**	**24**	**13**	**0.16**
25	1	17	17	55	24	0.04
25	2	10	27	36	18	0.11
25	3	14	41	26	13	0.14
25	**4**	**59**	**95**	**14**	**7**	**0.18**

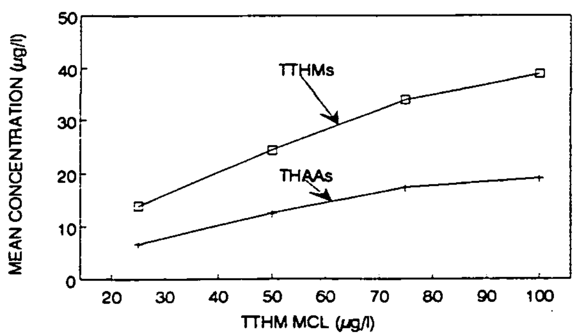
Percentage of Systems Using GAC



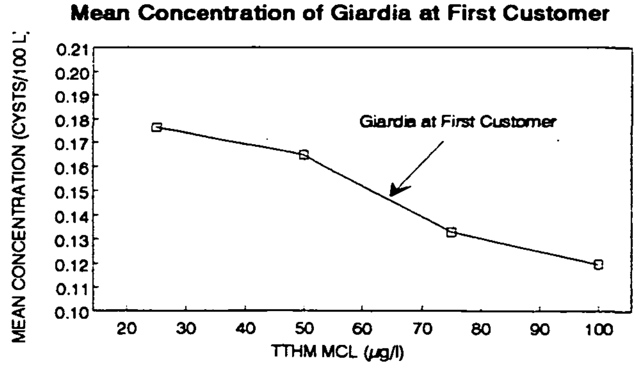
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs at Average Customer



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems installing each treatment tier
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

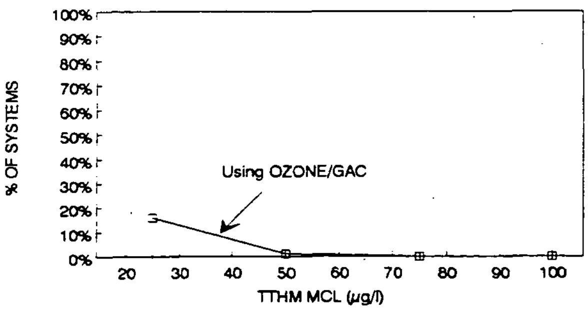
Figure 8

MODEL OUTPUT (surface w/o softening): SWTR W/ ALTERNATIVE DISINFECTION

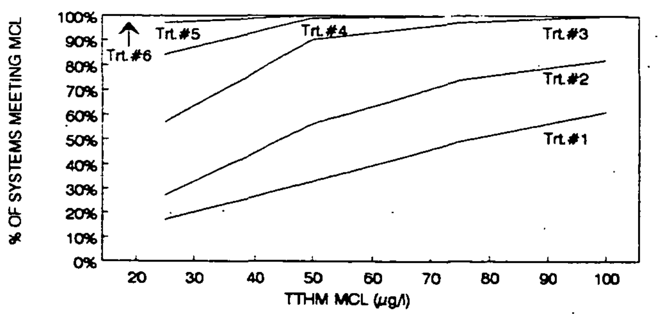
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

TTHM MCL [1] (µg/l)	Treatment Code	% of Sys. Ending [2]	Cumulative Percentage of Systems < MCL [3]	Mean Concentrations of By-Products at Avg.Cus. (µg/l) [4] TTHMs	THAAs	Mean Concentration of Giardia at First Customer [4] (cysts/100 L)
100	1	61	61	55	24	0.04
100	2	21	82	42	20	0.08
100	3	18	100	40	20	0.12
100	4	0	100	40	20	0.12
100	5	0	100	40	20	0.12
100	**6**	**0**	**100**	**40**	**20**	**0.12**
75	1	49	49	55	24	0.04
75	2	25	74	39	19	0.09
75	3	23	97	34	19	0.13
75	4	3	100	33	19	0.13
75	5	0	100	33	19	0.13
75	**6**	**0**	**100**	**33**	**19**	**0.13**
50	1	33	33	55	24	0.04
50	2	23	56	37	18	0.11
50	3	34	90	28	17	0.15
50	4	9	99	26	16	0.16
50	5	1	100	25	16	0.16
50	**6**	**0**	**100**	**25**	**16**	**0.16**
25	1	17	17	55	24	0.04
25	2	10	27	36	18	0.11
25	3	30	57	23	16	0.16
25	4	27	84	17	13	0.17
25	5	13	97	15	12	0.18
25	**6**	**3**	**100**	**15**	**12**	**0.18**

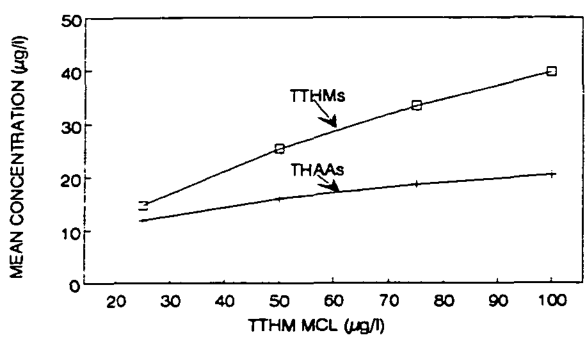
Percentage of Systems Using OZONE/GAC



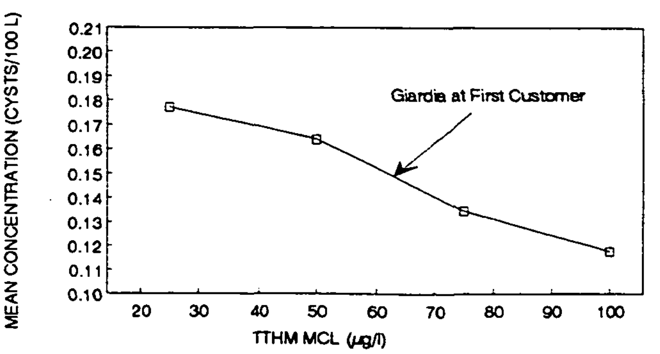
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs at Average Customer



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems installing each treatment tier
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Figure 9

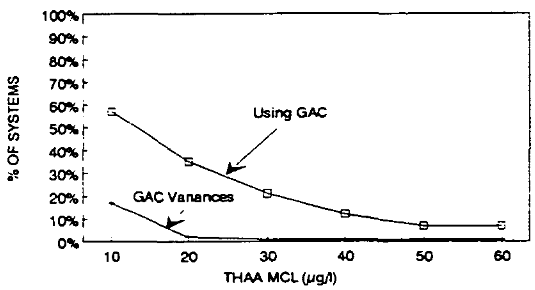
MODEL OUTPUT (surface w/o softening): SWTR W/O ALTERNATIVE DISINFECTION

Treatment Code:

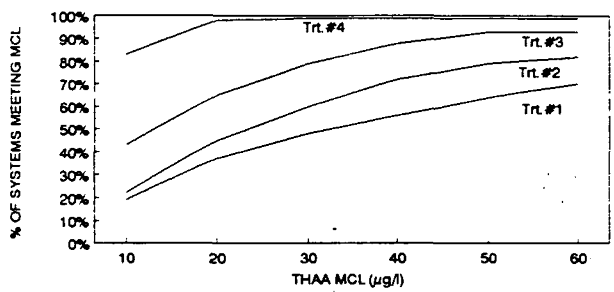
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

THAA MCL [1] (µg/l)	Treatment Code	% of Sys. Ending [2]	Cumulative Percentage of Systems < MCL [3]	Mean Concentrations of By-Products at Avg.Cus. (µg/l) [4]: TTHMs	THAAs	Mean Concentration of Giardia at First Customer [4] (cysts/100 L)
60	1	70	70	55	24	0.04
60	2	12	82	46	21	0.08
60	3	11	93	44	20	0.08
60	**4**	**7**	**99**	**43**	**19**	**0.08**
50	1	64	64	55	24	0.04
50	2	15	79	45	20	0.09
50	3	14	93	43	19	0.09
50	**4**	**7**	**99**	**41**	**19**	**0.09**
40	1	56	56	55	24	0.04
40	2	16	72	42	19	0.09
40	3	16	88	39	17	0.10
40	**4**	**12**	**99**	**36**	**16**	**0.10**
30	1	48	48	55	24	0.04
30	2	12	60	40	19	0.10
30	3	19	79	35	16	0.11
30	**4**	**21**	**99**	**30**	**12**	**0.11**
20	1	37	37	55	24	0.04
20	2	8	45	39	18	0.11
20	3	20	65	31	14	0.14
20	**4**	**35**	**98**	**24**	**9**	**0.14**
10	1	19	19	55	24	0.04
10	2	3	22	38	18	0.11
10	3	21	43	28	13	0.14
10	**4**	**57**	**83**	**17**	**6**	**0.17**

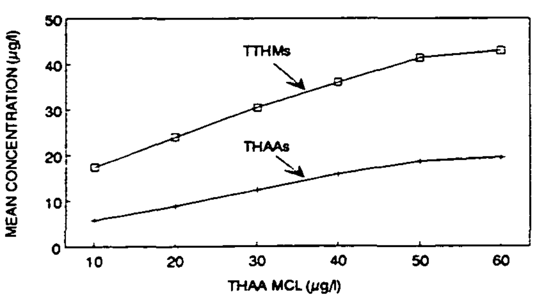
Percentage of Systems Using GAC



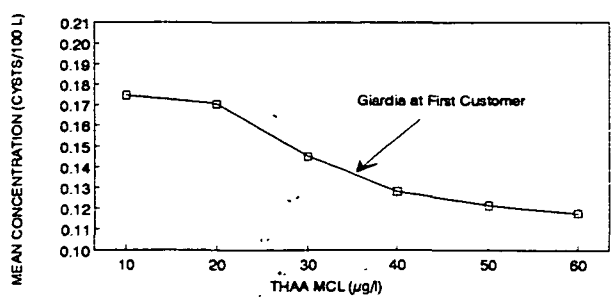
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems installing each treatment tier
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Figure 10

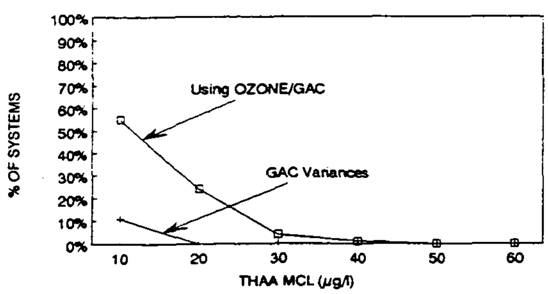
MODEL OUTPUT (surface w/o softening): SWTR W/ ALTERNATIVE DISINFECTION

Treatment Code:

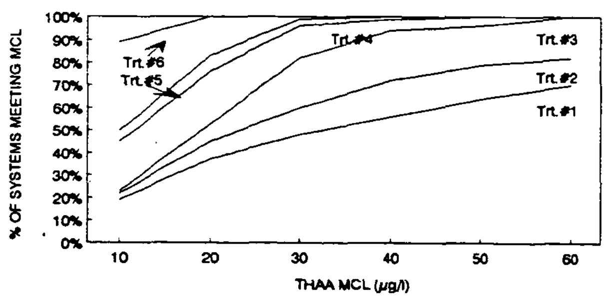
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

THAA MCL [1] (μg/l)	Treatment Code	% of Sys. Ending [2]	Cumulative Percentage of Systems < MCL [3]	Mean Concentrations of By-Products at Avg.Cus. (μg/l) [4] TTHMs	THAAs	Mean Concentration of Giardia at First Customer [4] (cysts/100 L)
60	1	70	70	55	24	0.04
60	2	12	82	46	21	0.08
60	3	18	100	43	21	0.07
60	4	0	100	43	21	0.07
60	5	0	100	43	21	0.07
60	**6**	**0**	**100**	**43**	**21**	**0.07**
50	1	64	64	55	24	0.04
50	2	15	79	45	20	0.09
50	3	17	96	42	20	0.08
50	4	4	100	41	20	0.08
50	5	0	100	41	20	0.08
50	**6**	**0**	**100**	**41**	**20**	**0.08**
40	1	56	56	55	24	0.04
40	2	16	72	42	19	0.09
40	3	22	94	38	18	0.09
40	4	5	99	36	18	0.10
40	5	1	100	36	17	0.10
40	**6**	**0**	**100**	**36**	**17**	**0.10**
30	1	48	48	55	24	0.04
30	2	12	60	40	19	0.10
30	3	22	82	34	17	0.10
30	4	14	96	30	15	0.11
30	5	3	99	30	15	0.11
30	**6**	**1**	**100**	**29**	**15**	**0.11**
20	1	37	37	55	24	0.04
20	2	8	45	39	18	0.11
20	3	8	53	29	16	0.12
20	4	23	76	23	13	0.14
20	5	7	83	22	12	0.14
20	**6**	**17**	**100**	**20**	**10**	**0.14**
10	1	19	19	55	24	0.04
10	2	3	22	38	18	0.11
10	3	1	23	26	16	0.16
10	4	22	45	18	12	0.17
10	5	5	50	15	10	0.20
10	**6**	**50**	**89**	**12**	**6**	**0.20**

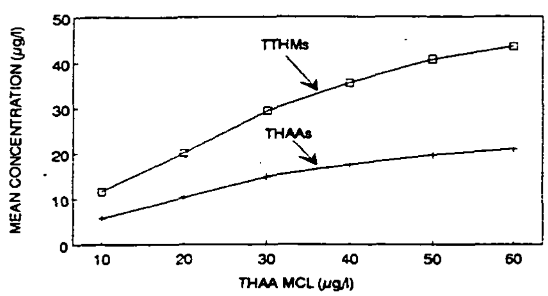
Percentage of Systems Using OZONE/GAC



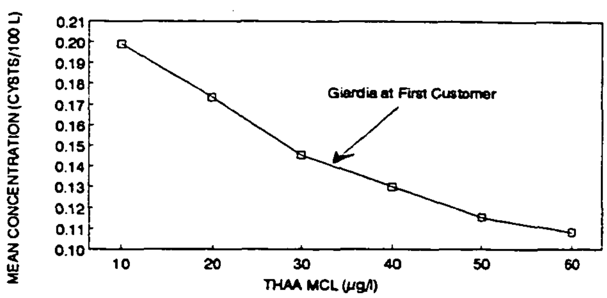
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems installing each treatment tier
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

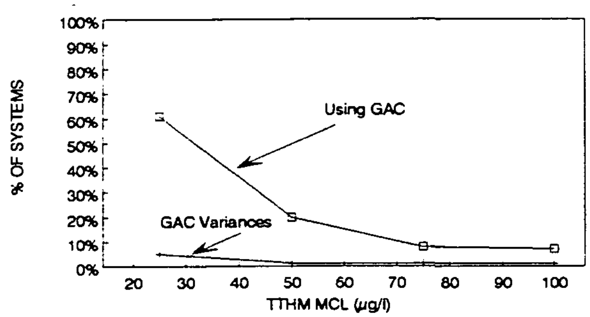
Figure 11

MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/O ALTERNATIVE DISINFECTION

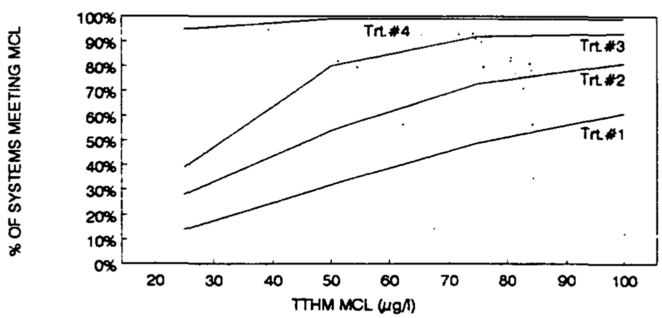
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre–chlorination
3 – eliminate pre–chlor + modify alum dose
4 – pre–chlor + alum dose + GAC

TTHM MCL [1] (µg/l)	Treatment Code	% of Sys. Ending [2]	Cumulative Percentage of Systems < MCL [3]	Mean Concentrations of By–Products at Avg.Cus. (µg/l) [4]		Mean Concentration of Giardia at First Customer [4] (cysts/100 L)
				TTHMs	THAAs	
100	1	61	61	57	25	8.0E–05
100	2	20	81	44	21	9.0E–05
100	3	12	93	41	20	9.2E–05
100	**4**	**7**	**99**	**40**	**19**	**9.0E–05**
75	1	49	49	57	25	8.0E–05
75	2	24	73	41	20	9.9E–05
75	3	19	92	36	18	1.0E–04
75	**4**	**8**	**99**	**34**	**18**	**9.9E–05**
50	1	32	32	57	25	8.0E–05
50	2	22	54	39	19	1.0E–04
50	3	26	80	30	15	1.1E–04
50	**4**	**20**	**99**	**25**	**13**	**1.1E–04**
25	1	14	14	57	25	8.0E–05
25	2	14	28	37	19	1.0E–04
25	3	11	39	26	13	1.1E–04
25	**4**	**61**	**95**	**14**	**7**	**1.1E–04**

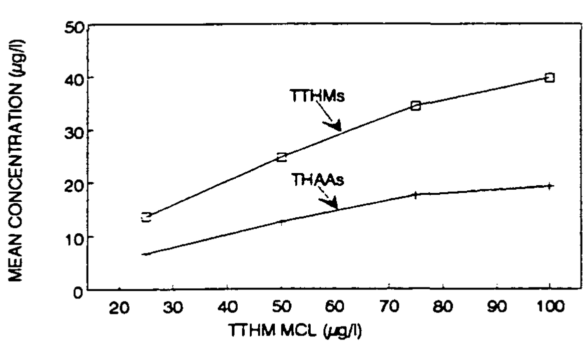
Percentage of Systems Using GAC



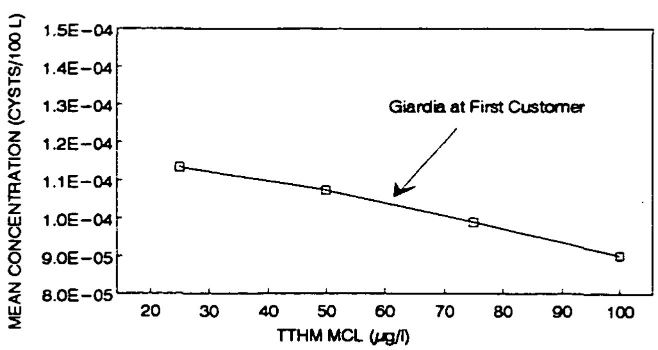
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs at Average Customer



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems *installing each treatment tier*
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

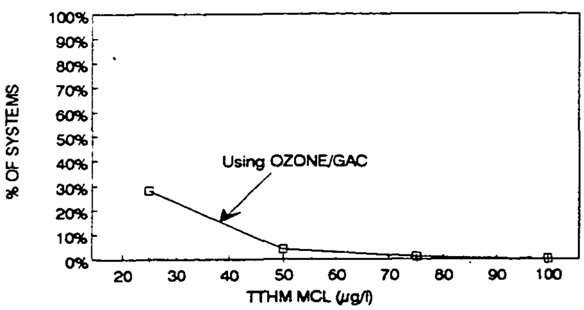
Figure 12

MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/ ALTERNATIVE DISINFECTION

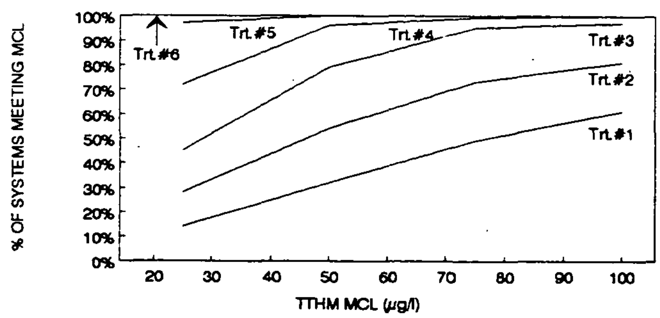
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

TTHM MCL [1] (μg/l)	Treatment Code	% of Sys. Ending [2]	Cumulative Percentage of Systems < MCL [3]	Mean Concentrations of By-Products at Avg.Cus. (μg/l) [4]		Mean Concentration of Giardia at First Customer [4] (cysts/100 L)
				TTHMs	THAAs	
100	1	61	61	57	25	8.0E-05
100	2	20	81	44	21	9.0E-05
100	3	16	97	43	22	9.3E-05
100	4	3	100	41	21	9.3E-05
100	5	0	100	41	21	9.3E-05
100	**6**	**0**	**100**	**41**	**21**	**9.3E-05**
75	1	49	49	57	25	8.0E-05
75	2	24	73	41	20	9.9E-05
75	3	22	95	38	20	1.0E-04
75	4	4	99	36	20	1.0E-04
75	5	1	100	36	20	1.0E-04
75	**6**	**0**	**100**	**36**	**20**	**1.0E-04**
50	1	32	32	57	25	8.0E-05
50	2	22	54	39	19	1.0E-04
50	3	25	79	33	19	1.1E-04
50	4	17	96	27	17	1.1E-04
50	5	4	100	26	16	1.1E-04
50	**6**	**0**	**100**	**26**	**16**	**1.1E-04**
25	1	14	14	57	25	8.0E-05
25	2	14	28	37	19	1.0E-04
25	3	17	45	29	18	1.1E-04
25	4	27	72	19	14	1.1E-04
25	5	25	97	15	12	1.1E-04
25	**6**	**3**	**100**	**15**	**12**	**1.1E-04**

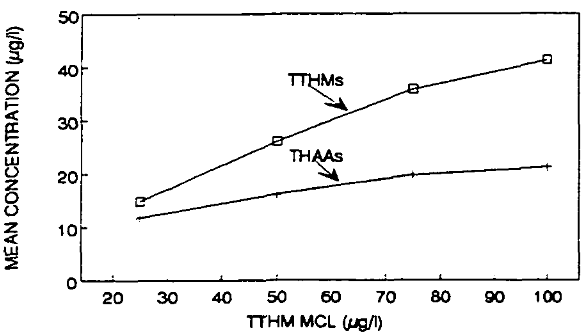
Percentage of Systems Using OZONE/GAC



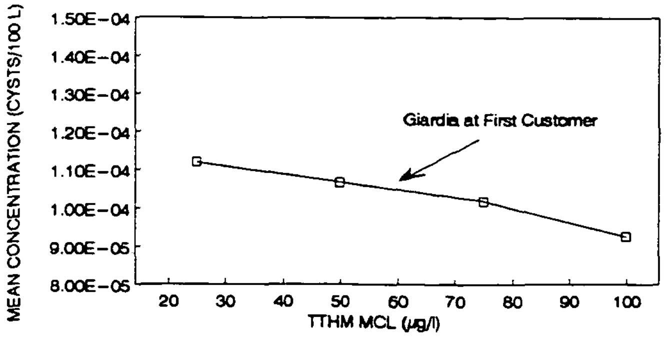
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs at Average Customer



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems installing each treatment tier
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Figure 13

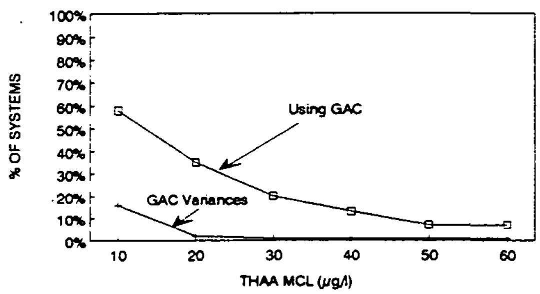
MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/O ALTERNATIVE DISINFECTION

Treatment Code:

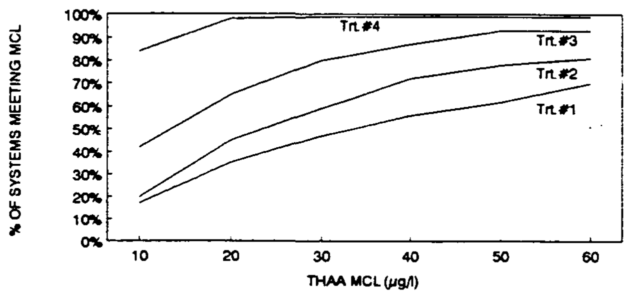
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

THAA MCL [1] (µg/l)	Treatment Code	% of Sys. Ending [2]	Cumulative Percentage of Systems < MCL [3]	Mean Concentrations of By-Products at Avg.Cus. (µg/l) [4]		Mean Concentration of Giardia at First Customer [4] (cysts/100 L)
				TTHMs	THAAs	
60	1	70	70	57	25	8.0E-05
60	2	11	81	48	21	9.0E-05
60	3	12	93	45	20	9.0E-05
60	**4**	**7**	**99**	**44**	**20**	**8.8E-05**
50	1	62	62	57	25	8.0E-05
50	2	16	78	46	21	9.3E-05
50	3	15	93	43	19	9.3E-05
50	**4**	**7**	**99**	**42**	**19**	**9.2E-05**
40	1	56	56	57	25	8.0E-05
40	2	16	72	44	20	9.7E-05
40	3	15	87	40	18	9.8E-05
40	**4**	**13**	**99**	**37**	**16**	**9.7E-05**
30	1	47	47	57	25	8.0E-05
30	2	12	59	42	19	1.0E-04
30	3	21	80	36	16	1.1E-04
30	**4**	**20**	**99**	**31**	**13**	**1.1E-04**
20	1	35	35	57	25	8.0E-05
20	2	10	45	40	19	1.0E-04
20	3	20	65	32	14	1.1E-04
20	**4**	**35**	**98**	**24**	**9**	**1.1E-04**
10	1	17	17	57	25	8.0E-05
10	2	3	20	39	19	1.0E-04
10	3	22	42	28	13	1.1E-04
10	**4**	**58**	**84**	**17**	**6**	**1.1E-04**

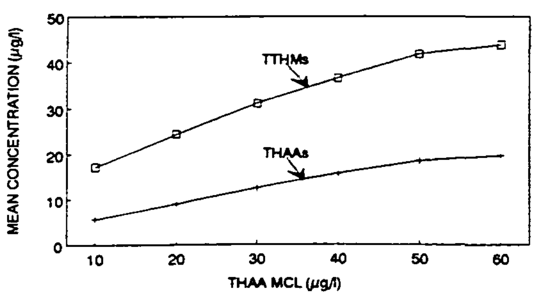
Percentage of Systems Using GAC



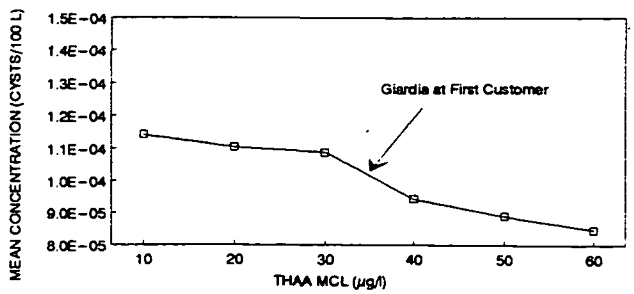
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems installing each treatment tier
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Figure 14

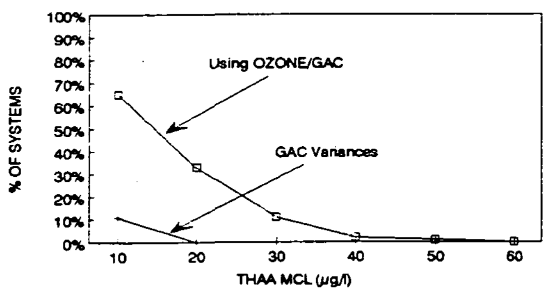
MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/ ALTERNATIVE DISINFECTION

Treatment Code:

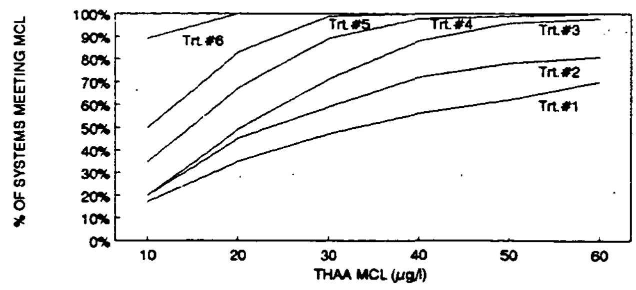
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

THAA MCL [1] (µg/l)	Treatment Code	% of Sys. Ending [2]	Cumulative Percentage of Systems < MCL [3]	Mean Concentrations of By-Products at Avg.Cus. (µg/l) [4]		Mean Concentration of Giardia at First Customer [4] (cysts/100 L)
				TTHMs	THAAs	
60	1	70	70	57	25	8.0E-05
60	2	11	81	48	21	9.0E-05
60	3	17	98	46	22	9.1E-05
60	4	2	100	45	22	9.1E-05
60	5	0	100	45	22	9.1E-05
60	**6**	**0**	**100**	**45**	**22**	**9.1E-05**
50	1	62	62	57	25	8.0E-05
50	2	16	78	46	21	9.3E-05
50	3	18	96	44	21	9.3E-05
50	4	3	99	43	20	9.3E-05
50	5	1	100	42	20	9.3E-05
50	**6**	**0**	**100**	**42**	**20**	**9.3E-05**
40	1	56	56	57	25	8.0E-05
40	2	16	72	44	20	9.7E-05
40	3	16	88	41	20	9.7E-05
40	4	10	98	38	18	9.8E-05
40	5	2	100	37	18	9.8E-05
40	**6**	**0**	**100**	**37**	**18**	**9.8E-05**
30	1	47	47	57	25	8.0E-05
30	2	12	59	42	19	1.0E-04
30	3	12	71	37	19	1.1E-04
30	4	18	89	32	16	1.1E-04
30	5	10	99	30	15	1.1E-04
30	**6**	**1**	**100**	**30**	**15**	**1.1E-04**
20	1	35	35	57	25	8.0E-05
20	2	10	45	40	19	1.0E-04
20	3	4	49	33	18	1.1E-04
20	4	18	67	26	14	1.1E-04
20	5	16	83	23	12	1.1E-04
20	**6**	**17**	**100**	**21**	**10**	**1.1E-04**
10	1	17	17	57	25	8.0E-05
10	2	3	20	39	19	1.0E-04
10	3	0	20	31	18	1.1E-04
10	4	15	35	21	13	1.1E-04
10	5	15	50	16	10	1.1E-04
10	**6**	**50**	**89**	**12**	**6**	**1.1E-04**

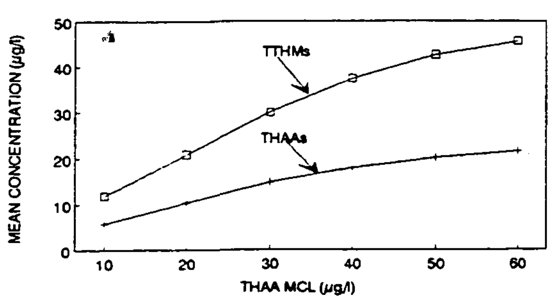
Percentage of Systems Using OZONE/GAC



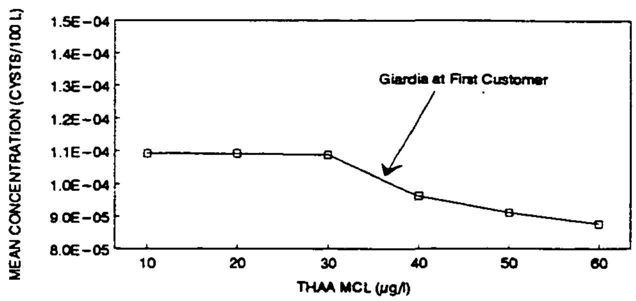
Percentage of Systems Meeting MCL



Mean Concentrations of DBPs



Mean Concentration of Giardia at First Customer



[1] respective MCLs include a 20% safety factor
[2] percent of systems installing each treatment tier
[3] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% safety factor for MCLs)
[4] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL