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A FRAMEWORK FOR EVALUATING SORBENT USAGE RATE OF VARIOUS SORPTION COLUMN CONFIGURATIONS WITH AND WITHOUT BYPASS BLENDING

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A FRAMEWORK FOR EVALUATING SORBENT USAGE RATE OF VARIOUS SORPTION COLUMN CONFIGURATIONS WITH AND WITHOUT BYPASS BLENDING

By

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Sorption systems are a prevalent technology in the field of environmental engineering for treating waters contaminated with organic and/or inorganic compounds. Examples of such contaminants include taste and odor, hardness, disinfection byproduct precursors, and arsenic.

The primary operating costs for these sorption systems lie in sorbent replacement. Different column arrangements and the use of bypass blending have the potential to reduce sorbent usage. Thus, this research aimed to develop a decision framework to assist engineers and practitioners in considering when to apply single columns, parallel columns, and lead-lag series configurations, with and without bypass, based on sorbent usage rate. This framework utilized two parameters that were found to influence the overall performance of each configuration option. These parameters were a normalization of the breakthrough curve, expressed as a ratio of the mass transfer zone length to the lag length (MTZ:Lag), and the normalized treatment objective (C/C_o). Based on these parameters, comparisons of the performance of various configurations, both with and without bypass, could be developed.

The following conclusions were formed based on this research:

- Systems operated at low MTZ:Lag ratios have the ability to yield significant savings in sorbent usage with the use of bypass over arrangements without bypass in single column or lead-lag arrangements.
- Systems with high MTZ:Lag ratios can benefit from the use of a lead-lag series configuration to increase column bed life and reduce sorbent usage rate, with or without bypass.
- Parallel column configurations can offer significant savings in sorbent usage, particularly in systems with higher treatment objectives and high MTZ:Lag ratios.
- Single column configurations without bypass remain competitive with other configurations for systems with low MTZ:Lag ratios (< about 0.5) and low treatment objectives (<0.2).

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CHAPTER 1: INTRODUCTION

1.1. Background

Sorption systems continue to be a common form of water treatment for myriad applications, including removal of synthetic organic compounds, natural organic matter, disinfection byproduct precursors, and heavy metals, among others (Crittenden et al., 2005). Sorption system media include, but are not limited to, granular activated carbon (GAC), granular ferric hydroxide (GFH), ion-exchange resins, activated alumina, and others. Although these systems require relatively low levels of maintenance, sorbent replacement costs often constitute a large portion of operating costs (Narbaitz and Benedek, 1983; Adams et al., 1989; Clark and Adams, 1991; Hyun, 2004). As a result, previous work has investigated the use of various column configurations to improve the efficiency of such treatment systems (Denning and Dvorak, 2009; Dvorak, et al., 2008; New, 2009).

Comparing sorbent usage for a single column; a two, six, and infinite parallel column; and a lead-lag series configuration, Denning and Dvorak (2009) developed a configuration selection diagram (CSD) to assist engineers in consideration of each configuration option. To develop the CSD, two parameters were identified as significant and predictive in the comparison of column configurations; the percentage of the column occupied by the mass transfer zone (%MTZ) and the normalized treatment objective (C/C_o). Based on these parameters, specific scenarios where a particular column configuration outperformed the others could be identified. This research also began the investigation into the incorporation of bypass blending, finding that parallel columns with bypass yielded little benefit, while lead-lag systems with bypass could produce considerable sorbent usage improvements (Denning and Dvorak, 2009). New (2009) then provided a preliminary study of how bypass blending could be incorporated into a theoretical framework for considering when each column configuration would yield the lowest sorbent usage rate. New's research (2009) led to this further investigation into the potential benefits of bypass blending for sorption systems.

1.2. Objective

To expand on the work of Dvorak et al. (2008), Denning and Dvorak (2009), and New (2009), this research aims to investigate potential improvements in sorbent usage rate, comparing single columns with and without bypass, lead-lag series with and without bypass, and two-column parallel configurations without bypass. The primary objective of these comparisons is to develop a framework for consideration of the configurations listed above to assist engineers and practitioners when evaluating different options for design and operation. Evaluation of column performance is based on reductions in sorbent usage rate for systems operating at a range of normalized treatment objectives, and with a variety of breakthrough curve shapes (normalized as a ratio of MTZ length to lag length, or MTZ:Lag). The MTZ of a breakthrough curve is defined as the difference in time between reaching a normalized column effluent concentration (C/C_o) of 0.05 and 0.95. The lag period is the time taken for the MTZ to reach the column effluent, or for the column effluent C/C_o to reach 0.05 (Hand et al., 1984; Crittenden et al., 1987).

1.3. Thesis Organization

A review of literature pertinent to this study can be found in Chapter 2, discussing the software and mathematical models used to simulate the different scenarios, the basis for the different contaminant-sorbent pairs modeled, and some common conventions in water treatment where the principles developed in this study can be found in practice. Chapter 3 provides the primary findings of this research following the format of a journal article. The intent is for Chapter 3 to be submitted a journal for possible publication. Finally, Chapter 4 provides the conclusions of this research and several possible directions for further study. Appendices include further information and data for the different scenarios, simulations, and results.

CHAPTER 2: SORPTION MODELING OVERVIEW AND LITERATURE

2.1. Introduction

To provide a greater understanding of the origins of this study, several topics will be discussed. This overview will provide some background related to the mathematical process models and software used to perform simulations. The sources of information used to develop parameters for the specific simulations performed in this study will be explained. Finally, several real world situations applying the ideas presented in this study will be included to provide greater perspective on the different applications of this study's results.

2.2. Mathematical Modeling of Adsorption

Adsorption behavior was modeled using the Adsorption Design Software (AdDesignS) developed by the National Center for Clean Industrial and Treatment Technologies at Michigan Technological University in 1994 (Mertz et al., 1999). This software, developed and authored by David Hokanson, David Hand, John Crittenden, Tony Rogers, and Eric Oman, provides an interface for user inputs and application of several options of mathematical models to simulate breakthrough curves for myriad contaminant-adsorbent pairs including the pore surface diffusion model (PSDM) and the constant pattern homogeneous surface diffusion model (CPHSDM) (Hokanson et al., 1999a).

For the purposes of this research the pore surface diffusion model (PSDM) was used to simulate adsorption behavior between model contaminant and adsorbent. This model has been found to be an effective method with which to model adsorption of synthetic organic contaminants (SOCs) in GAC columns (Hand et al., 1997). Other researchers have also found the PSDM useful in simulating adsorption systems in various situations (e.g. Fritz et al., 1980; Zimmer et al., 1988; Hand et al., 1989; Magnuson and Speth, 2005; Hristovski et al., 2008a and 2008b). By accounting for both pore and surface diffusion, the PSDM is referred to as "the most comprehensive mass transfer model" by Hand et al. (1997) and has been utilized to model an array of systems including newer technologies such as sorption of arsenate with zirconium oxide-based media in Hristovski et al. (2008b).

The PSDM utilizes two partial differential equations (PDEs) to develop mass balances for liquid- and solid-phase adsorption. A coupling equation makes the assumption of equilibrium at the surface of the media. Using the orthogonal collocation method the PDEs are converted to ordinary differential equations (ODEs) that can then be solved using Gear's stiff method. Friedman (1984), Sontheimer et al. (1988) and Crittenden et al. (1980 and 1986) provide more information on the mathematics of the PSDM.

To utilize the PSDM, properties and adsorption parameters of the contaminant(s) were imported to AdDesignS as it was developed. For many commonly encountered contaminants the Software to Estimate Physical Properties (StEPP), also developed at the Center for Clean Industrial and Treatment Technologies at Michigan Technological University, can be used. Authored by David Hokanson, Tony Rogers, David Hand, Michael Miller and John Crittenden, StEPP is intended for use with AdDesignS to provide contaminants' physical properties necessary to simulate breakthrough curves with the PSDM in AdDesignS (Hokanson et al., 1999b). Properties acquired from StEPP are easily copied and pasted into AdDesignS for breakthrough curve simulation. Updates to existing contaminants and properties of contaminants not already available in StEPP can be input manually. In this study, properties for Benzene were acquired from StEPP while physical properties of Arsenate were found in other literature (Hristovski et al., 2008a; USDHHS, 2000).

Following the methods outlined by New (2009), once the model contaminant and adsorbent are identified and entered into the software, adsorption kinetics and equilibrium isotherm values, apparent density, particle radius, porosity, and particle shape factor can all be adjusted by the user. Additionally, column parameters can be manually entered, such as column length, diameter, flow rate, empty bed contact time (EBCT), and bed mass. Column length and EBCT were changed in order to adjust the MTZ length and correspondingly alter the MTZ:Lag ratio. By decreasing column length and EBCT, the MTZ began sooner (shorter lag) and the MTZ:Lag ratio was raised (New, 2009).

AdDesignS allows for modeling competition between different contaminants within a column. Due to the fact that competitive adsorption did not conform well to the normalization used in this study, adsorption competition was not taken into consideration. Denning and Dvorak (2009) investigated the role competition played in modeling adsorption column performance. Based on the solute distribution parameter (D_g) of each competing compound, the degree of competition between contaminants could be quantified. The findings of Denning and Dvorak (2009) indicated that when competition altered the MTZ significantly, the configuration selection diagram (CSD) could no longer be used as intended. Therefore, competition was not considered in this study. Instead, arsenate and benzene were modeled separately to examine a range of contaminants and ensure the basis for comparison was applicable to a range of situations.

2.3. Basis for Scenarios Modeled

Modeling of Calgon F400 GAC used to treat Benzene contaminated water was based on the work of Denning and Dvorak (2009) and New (2009). Denning and Dvorak (2009) developed a CSD examining the potential savings in sorbent usage when considering single columns, lead-lag series, or parallel column arrangements. New (2009) then built on the work of Denning and Dvorak (2009) to include bypass into the consideration and evaluate the possible savings. To model these scenarios, properties of Benzene were found in StEPP and imported to AdDesignS to be used as a model contaminant. Likewise, Freundlich isotherm constants and kinetics for Calgon F400 GAC were found in the AdDesignS adsorbent database and were then applied to the model.

Modeling of the Iron Hyrdoxide Modified GAC to treat arsenate contaminated water was derived from Hristovski, et al. (2008a). In this experiment two modified GACs were created using different treatment methods; Fe(III)/alcohol treatment method (M-3-15), and $KMnO_4$/Fe(II) treatment method (Mn-0.5-15). Adsorption capacities were then determined for the two modified GACs and fit to the Freundlich isotherm model based on batch experiments using an initial arsenate concentration of 120µg/L As(V) in 10 mM $NaHCO_3$ buffered ultrapure water. Short bed adsorber (SBA) column tests were then conducted at the same water quality as the batch experiments and were used to support the PSDM. Using the results of this study, the relevant properties and parameters needed to simulate column performance could be found and applied to this study as a new adsorbent/adsorbate pair to expand the results of New (2009). The two scenarios from Hristovski et al. (2008a) were recreated to verify similar results, and were then applied to this study to determine column performance in single column, lead-lag and parallel arrangements with and without bypass.

2.4. Column Configurations in Literature

Standard conventions described in the technical literature for column configurations, as well as real world applications are provided here to show how all of these fit within the framework proposed in this study. Ion-exchange/water-softening systems, GAC treatment of disinfection by-product (DBP) precursors, total organic carbon (TOC) and sorption of arsenate are a few examples of where principles of this study are being applied (Stevenson, 1997; Clark and Lykins, 1989; Dvorak and Maher, 1999; McGuire et al., 2002).

One common convention relates to ion-exchange systems. Ion-exchange water softening systems are a prevalent component in drinking water treatment. Due to the fact that water-softening systems often remove far more hardness than necessary, softening systems often incorporate bypass lines to maintain appropriate hardness. These systems often feature abrupt breakthrough curves (e.g., a short MTZ) and as a result may lead to significant improvements in treatment media usage when used with a bypass line (Stevenson, 1997). One example of such application was found in the city of Wapakoneta, OH where an ion-exchange softening system was used to remove hardness. Because, in this case, the ion-exchange system removed hardness to zero, a brine bypass of about 25% was incorporated to maintain the appropriate level of hardness (Hamel, 2011).

Another common convention is found in the use of GAC adsorption to remove DBP precursors and TOC. In these systems, higher C/C_o treatment goals and long MTZs make the use of bypass blending counterproductive. However, systems with long MTZs often benefit from the use of parallel column configurations as the MTZs can be staggered and the effluent is blended gradually. It is reported in the literature that this is often the case and GAC columns are often placed in parallel when used to treat DBP precursors and TOC (Clark and Lykins, 1989; Dvorak and Maher, 1999; McGuire et al., 2002).

In another example of adsorption treatment, granular iron media was used by Arizona American Water to treat arsenate in their water supply in four different treatment plants. These systems were designed to treat to target C/C_o levels of about 0.1 to 1.0. Each of these systems was operated with a relatively short MTZ, and by utilizing bypass in these systems, Arizona American Water reported a 40% to 60% reduction in sorbent usage rate (Mecham, 2010).

Finally, in several case studies published by Severn Trent Services, sorption systems were used to treat arsenate contaminated water in several communities. In these studies, removal rates ranged from 10% to 70%. Many of the systems described in these case studies were able to apply bypass when treating to C/C_o values of around 0.2 – 0.9. For example, in the community of Hilltown Township, PA, the water supply required treatment to remove arsenate from its groundwater. A sorption system was utilized to provide treatment with a target C/C_o, of 0.2. This system was able to incorporate the maximum bypass, or a percent bypass equal to the normalized effluent concentration, which in this case was a 20% bypass of untreated influent water while maintaining adequate water quality (Severn Trent Services, 2010a). A second application of bypass could be found in Twentynine Palms, CA. Again, in Twentynine Palms, the community needed to remove arsenic in its drinking water to a C/C_o value of 0.2 and was able to apply the maximum bypass of 20% (Severn Trent Services, 2010b). Finally, a third example of bypass blending was found in a treatment plant in Perkasie, PA. Here, a target C/C_o of 0.67-0.75 allowed the community to install a bypass line allowing up to 32% bypass of untreated influent flow (Severn Trent Services, 2010c). This situation highlights use of a bypass rate less than the maximum, which is not uncommon in practice and may provide benefits in factors such as risk and compliance. These examples of bypass blending in the treatment of arsenic with sorption systems present several treatment objectives and bypass rates. While the maximum bypass may be a viable option to improve sorbent usage, factors including MTZ and lag length, and treatment objective, among others, vary and will influence the best bypass rate for a given system.

2.5. Summary

To develop results for a variety of systems and configurations, the PSDM within AdDesignS was used to simulate breakthrough curves for specific scenarios. Parameters allowing for modeling of such scenarios were found in published literature and the StEPP program developed by Michigan Technological University. Finally, to highlight the applications of this study, several real world scenarios were discussed illustrating a variety of systems and scenarios where the results of this study applied.

CHAPTER 3: EVALUATION OF VARIOUS COLUMN CONFIGURATIONS

3.1. Introduction

The use of sorption systems continues to increase in prevalence in water treatment applications. Examples of such systems include activated alumina used to remove fluoride; ferric hydroxide to remove arsenic; cation- and anion- exchange resins used for water softening, uranium and nitrate removal; and granular activated carbon (GAC) to remove organic and inorganic contaminants. Because sorbent costs typically contribute a large portion of total operating costs of these systems, alternatives to improve sorbent use should be explored to assist engineers in the design of more efficient systems (e.g., Narbaitz and Benedek, 1983; Clark and Adams, 1991).

This research builds on work by Denning and Dvorak (2009), Dvorak et al. (2008), and New (2009) in which the authors developed the concept of a Configuration Selection Diagram (CSD). The CSD is a framework for comparing the sorbent use of different sorption column configurations to aid the design engineer in selecting the best sorption system configuration. This study extends their work to include bypass blending in a comparison framework of single columns, lead-lag, and parallel column configurations.

The simplest of the column configurations is a single column, where contaminant-laden water (influent) is fed into the column and the contaminant is transferred from the liquid phase to the solid phase through the sorption process. As the mass transfer zone (MTZ) travels through the column and sorbent is used, the column effluent concentration eventually rises and reaches the target treatment goal, at which point the sorbent is replaced.

Lead-lag configurations involve placing two single columns in series where influent is first fed into the lead column and then flows through the lag column. Here the MTZ travels through both columns until the lag column effluent reaches the treatment objective. The sorbent in the lead column is then replaced and the new column is moved to the lag position. This lead-lag rotation is repeated, with columns switching places in the configuration as the effluent concentration from each lag column reaches the treatment objective.

A parallel configuration consists of two or more identical single columns that are fed the same influent in equal proportions, and the effluent is blended before discharge. If the mass transfer zones of each column are staggered, parallel configurations will, in some circumstances, outperform other configurations, particularly at high normalized treatment objectives when no bypass is involved (Denning and Dvorak, 2009).

Published research on sorption focuses on maximizing the utilization of sorbent in a column by determining which configurations of columns (such as single column, lead-lag and parallel columns) work the best for a given set of conditions. Such work dates back to Hutchins (1977), and Crittenden et al. (1987) who characterized the efficiency of various configurations based on two sets of parameters: the MTZ and the maximum effluent concentration which is the target treatment goal. The parameters upon which these researchers have based their conclusions include (1) the ratio of the length of the MTZ to the length of the column (also expressed as percent mass transfer zone or

%MTZ), and (2) the target treatment goal expressed as the ratio of the effluent concentration to the influent concentration (expressed as C/C_o).

Little attention has been given to a theoretical evaluation and framework for bypass blending. In this scenario, a portion of the influent is bypassed around a particular sorption configuration (e.g., lead-lag or single columns), and subsequently blended with the column effluent prior to discharge. Bypass is particularly applicable when the sorption column configuration can produce much better water quality than required. Often this is the case when a new sorption column is placed in service: the initial effluent concentration is zero, while the target treatment goal is somewhere above zero. Additionally, because a portion of the influent flow is diverted, bypass blending can reduce the flow through the column and, consequently, the required column size. This has the potential of reducing both the capital and sorbent replacement costs for a given treatment capacity.

Denning and Dvorak (2009) briefly explored bypass blending with single, lead-lag, and parallel columns but did not incorporate bypass into their CSD framework; they found that while there was little benefit in bypass blending with parallel columns, significant benefit may be possible when incorporating bypass with lead-lag and single column configurations. The wide range of mass transfer zone sizes and removal rates that occur in environmental engineering practice indicate a need for evaluation of configuration performance based on the aforementioned parameters. Thus, the goal of this work is to build upon that of Denning and Dvorak (2009) to refine and solidify parameters for creating a framework based on breakthrough curve shape and treatment objective to assist engineers and practitioners in comparing column performance of single columns, lead-lag series, and parallel columns both with and without bypass.

3.2. Methods

A sorption model was used to simulate different contaminant-sorbent scenarios for a wide range of column sizes and configurations for this study, given the limited available pilot- or full-scale sorption breakthrough data for column configuration comparisons in the technical literature (Denning and Dvorak, 2009; New, 2009).

3.2.1. Chromatographic Breakthrough Front Modeling.

Two fundamental aspects of the chromatography for single contaminant systems are factored into the results of this study; the mass transfer zone (MTZ) and the lag period. The first aspect, the MTZ, is the portion of the sorption column where sorption is taking place at a given time. Behind the MTZ, the liquid phase concentration (normalized as C/C_o) equals 1.0 as the sorbent has been saturated with contaminant. In front of the MTZ, the liquid phase concentration is 0 and the sorbent has not yet been exposed to the contaminant. For the calculations in this study, the MTZ is defined as the distance or time between C/C_o = 0.05 and 0.95 following Hand et al. (1984) and Crittenden et al. (1987).

The second parameter, the lag period, is defined for this study as the time it takes for the beginning of the MTZ to reach the effluent zone, or for effluent C/C_o to reach 0.05. The lag period, not to be confused with the lag column in a lead-lag configuration, is primarily a function of the column length, empty bed contact time (EBCT) and sorption kinetics among other factors.

Lag and MTZ zones of two distinctly different breakthrough curves are shown in Figure 3.1. The x- axis represents the normalized bed life, which is defined as a ratio of run time, to the bed life. And the y-axis is the normalized effluent concentration C/C_o. The normalization of both axes yields a normalized bed life of one when C/C_o reaches 0.5. The two profiles illustrate the differences between a gradual MTZ, here shown with a long MTZ resulting in a MTZ:Lag ratio of 1.33, and a sharp MTZ, here with a MTZ:lag ratio of 0.13.

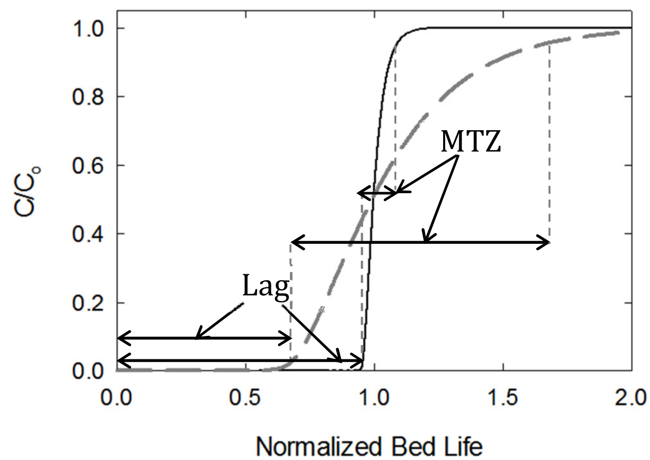

Figure 3.1. Illustration of Lag and MTZ Phase of Single Column Breakthrough Curves for a Long and Short MTZ

A decision framework for comparing various column configurations with and without bypass blending, and design parameters, requires the use of normalized axes.

For conventional configurations, Denning and Dvorak (2009) were able to plot relative column performance on a graph of %MTZ (the percentage of the column length occupied by the MTZ) vs. target effluent C/C_o. With bypass, it was found that not only did the MTZ factor into column performance, but the lag length played a role as well.

Ultimately, it was found that the ratio of the MTZ length and lag length was the most reliable parameter plotted versus the target effluent C/C_o.

3.2.2. Sorption Modeling

The Pore Surface Diffusion Model (PSDM) (Crittenden et al., 1980) within the AdDesignS™ software (Hokanson et al., 1999a) was used to simulate sorption breakthrough from the columns. Other researchers have found the PSDM useful in accurately simulating various sorption systems to fit breakthrough curves (e.g., Fritz et al., 1980; Zimmer et al., 1988; Hand et al., 1989; Hristovski et al., 2008). Many of the properties for contaminants and their parameters were obtained from StEPP™ (Hokanson et al., 1999b), a chemical database created specifically for use with AdDesignS™. In addition, some sorbent parameters were obtained from the AdDesignS™ sorbent database, based on data provided by the sorbent manufacturer. The three scenarios modeled represent a range of possible treatment situations (e.g., equilibrium, mass transfer rates, adsorbent and adsorbate) to verify that the results could be applied to many sorption systems. PSDM and Freundlich isotherm parameters and data sources used for each of three scenarios simulated are listed in Table 3.1.

Table 3.1 – Model input parameters used for scenarios in this study

Parameter/**Scenario**	**A**	**B**	**C**
Adsorbent	Mn-0.5-15 Iron Hydroxide Modified GAC (1)	M-3-15 Iron Hydroxide Modified GAC (1)	Calgon F300 GAC (2)
Surface Loading $[m^3/(m^2 \cdot h)]$	12	12	6
Bed Density (g/mL)	0.3979 (1)	0.3979 (1)	0.4600 (3)
Apparent Density (g/mL)	2.00 g/mL (1)	2.00 g/mL (1)	0.480 g/mL (3)
Particle Radius (cm)	0.050 cm (1)	0.050 cm (1)	0.082 cm (3)
Porosity	0.78 (1)	0.78 (1)	0.65 (3)
Particle Shape Factor	1.2 (1)	1.2 (1)	1.0 (3)
Film Diffusion (cm/s)	6.2×10^{-3} (1)	5.5×10^{-3} (1)	8.6×10^{-3} (2)
Surface Diffusion (cm^2/s)	4.5×10^{-10} (1)	4.5×10^{-10} (1)	6.2×10^{-40} (2)
Pore Diffusion (cm^2/s)	3.67×10^{-6} (1)	3.67×10^{-6} (1)	7.6×10^{-6} (2)
Contaminant	Arsenate	Arsenate	Benzene
Freundlich K $[(mg/g)(L/mg)^{(1/n)}]$	2.60 (1)	1.01 (1)	16.6 (3)
Freundlich (1/n)	0.58 (1)	0.66 (1)	0.39 (3)

(1) - Hristovski, et al. (2008a)
(2) - New (2009)
(3) - Hokanson, et al. (1999a)

3.2.3. Column Configuration Simulation

Three conventional sorption configurations were simulated in this study: single columns, lead-lag, and two-column parallel. The simplest configuration is a single column. In this system, the effluent concentration is continuously monitored until it reaches the target treatment goal, at which point the column is pulled offline and the sorbent is replaced. In some situations, several columns are operated independently, each in a single column arrangement, with the flow divided among these columns yielding an influent flow rate of Q/n.

A lead-lag configuration involves two identical single columns placed in series. Influent enters at a flow rate, Q, in a fashion similar to that of a single column. However, with a lead-lag configuration, flow travels sequentially through the *lead* column and then the *lag* column. This allows for the exhaustion of the lead column sorbent before transferring the mass transfer zone to the lag column. This effectively extends the lag zone across both columns. Once the *lag* column concentration reaches the target treatment goal, the *lag* column is switched to the lead position and fresh sorbent is placed in the new *lag* column which was formerly in the lead position. This lead-lag rotation is repeated indefinitely.

A two-column parallel configuration employs two identical columns. Each column is fed half of the influent flow of Q/2. In parallel configurations, column operations are staggered by allowing a time interval between placing columns online, and thus delaying the MTZ of the second column. Unlike the independent operation of two single columns, the effluent flow from each column is blended prior to discharge allowing for blending of concentrations above and below the treatment objective, prolonging the bed life of each column.

Typical breakthrough curves for single column and parallel configurations are shown in Figures 3.2A and 3.2B. Figure 3.2A depicts the breakthrough curve for a single column configuration with 40% bypass and no bypass. Bypassing 40% of the untreated raw water raises the initial concentration for the blended effluent to a C/C_o of 0.4. The lead-lag breakthrough curve is similar to the single column, however, the time between sorbent replacement is longer than with single columns since lead-lag configurations effectively extend the lag time.

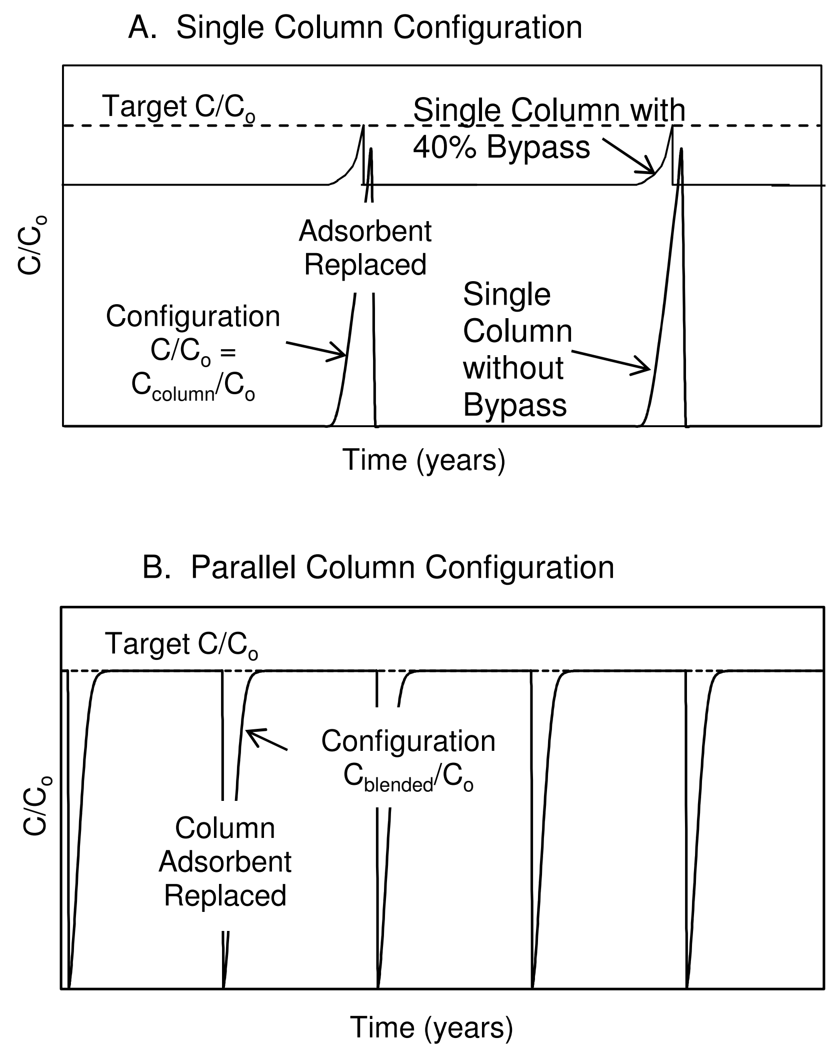

Figure 3.2. Effluent Curves for a Single Column Configuration with 40% Bypass and No Bypass (A); Parallel Configuration (B)

Figure 3.2B shows the breakthrough curve for a two-column parallel configuration with staggered MTZs. In this parallel configuration example, the target C/C_o is 0.5. Staggering the MTZs enables the columns to be operated so that one column C/C_o is at 1.0 while the other is at 0; the average effluent concentration is 0.5. Once the other column's effluent concentration rises above 0, the first column is replaced. Thus, the configuration's blended concentration typically remains at or near the target C/C_o.

It is worth noting that bypass blending with single columns and use of two parallel columns offer similar benefits in sorbent usage. By allowing more contaminant to pass into the effluent while maintaining a high blended concentration below the target, both systems behave similarly.

Bypass blending involves routing a portion of the untreated water, around the treatment column (or configuration) while the remainder is sent through the column (or configuration) for treatment. Treated water is then combined with the untreated bypass water and the blended concentration is kept below the treatment objective. The total flow, Q, is the sum of the column flow, Q_{column}, and the bypass flow, Q_{bypass}. The blended concentration is determined based on a mass balance at the point of blending between the treated flow and concentration in the column effluent, and the untreated bypass flow and concentration. Unless otherwise stated, bypass refers to a “constant bypass” where the bypass flowrate and concentration remained consistent for each simulated scenario.

It is important to note that the maximum proportion bypass (subsequently called maximum bypass in this study) is dependent on the target treatment goal (blended target C/C_o) and is the maximum bypass rate that meets the treatment objective. For example, the maximum bypass for a target C/C_o of 0.5 is 50%, as justified by Equation 3.1 where 50% of the influent is bypassed around the column while the column is treating to an effluent C/C_o of 0.0:

$$Q_{blended}\left({}^{C}/{}_{C_o}\right)_{blended} = Q_{bypass}\left({}^{C}/{}_{C_o}\right)_{bypass} + Q_{column}\left({}^{C}/{}_{C_o}\right)_{\substack{treated\ by\\ column}}$$
$$= 0.5Q(1.0) + 0.5Q(0.0) = Q(0.5) \qquad (3.1)$$

Any proportion bypass greater than the normalized target treatment goal would be inadequate because the blended effluent concentration $C_{blended}/C_o$, would always be above the target C/C_o. Maximum bypass differs from the best bypass option (called best bypass in this study) as best bypass is the bypass proportion approximately yielding the most efficient use of sorbent for a given system with a specific MTZ:Lag ratio and treatment objective. Best bypass is not necessarily the optimal bypass since bypass rates were limited to increments of 10% (e.g., 10%, 20%, etc.) in the modeling and analysis.

The use of the PSDM derived-breakthrough data and spreadsheets allowed for the overall determination of sorbent usage rates. To alter the MTZ:Lag ratio for a given scenario, column length was adjusted. For example, to increase the MTZ:Lag ratio, a shorter column was used, creating a shorter lag, and a longer MTZ as a percentage of the column length. Additionally, when incorporating bypass, column diameter was adjusted relative to the bypass rate. By reducing the column size when utilizing bypass the surface loading rate and EBCT remain constant. To model single columns, the AdDesignS™ breakthrough curve data were transferred into a spreadsheet and bed life was determined based on the target treatment goal. Modeling configurations other than single columns (i.e. lead-lag, parallel and bypass configurations) involved additional spreadsheet manipulation, the steps of which are described in New (2009).

3.2.4. Key Assumptions and Modeling Parameters

Several assumptions were applied to this study to develop the simulations to compare the systems using the PSDM model. The PSDM assumes a constant influent concentration (unless otherwise input by the user), constant flowrate, plug flow through the bed, and use of the Freundlich isotherm to describe sorption equilibrium of each contaminant. Following Denning and Dvorak (2009), this study assumed a constant breakthrough curve shape and velocity as it passed through the column. All breakthrough curves studied fit the logistic model of Clark (1987).

3.3. Results

3.3.1. Basic Configuration Comparisons

As previously discussed by others (Denning and Dvorak, 2009; Dvorak, et al., 2008) lead-lag and parallel column configurations can potentially yield a lower sorbent usage rate to achieve the treatment goals than single columns operated independently. To determine the potential for savings in sorbent usage made possible by utilizing the two columns in a lead-lag or parallel configuration as opposed to two single columns, the scenarios listed in Table 3.1 were modeled for a range of column sizes to determine sorbent usage rate (SUR) at a range of treatment objectives and MTZ lengths. As mentioned earlier, the MTZ:Lag ratio is a function of the contaminant, adsorbent, flow rate, and column size. Based on the assumptions used in this study, the MTZ shape and size is generally consistent for a given contaminant, sorbent and flow rate, regardless of column size. The lag period, however, can be shortened or extended by a decrease or increase in column length, respectively. SUR was used as the defining parameter for column performance and was calculated based on the mass of adsorbent in the column divided by the total amount of water processed for one bed life. Fractional utilization is also an important parameter for evaluating column performance. As a column is replaced before the effluent reaches the treatment objective, a portion of the sorbent is left unsaturated. The ratio of used sorbent to total sorbent in the column is the fractional utilization and is expressed as a percentage of the total sorbent in the column (Crittenden et al., 2005). Efficient operation of a column will result in a high fractional utilization and lower SUR.

Figure 3.3 presents SUR reductions for applying lead-lag or two-column parallel configurations as opposed to operating two equivalent single columns independently; none of these systems include bypass blending. The x-axis represents the normalized target effluent concentration (C/C_o) and the y-axis represents MTZ:Lag ratios. The comparison between lead-lag and single column arrangements without bypass (solid lines) shows that the largest benefit from applying a lead-lag configuration occurs at larger MTZ:Lag ratios.

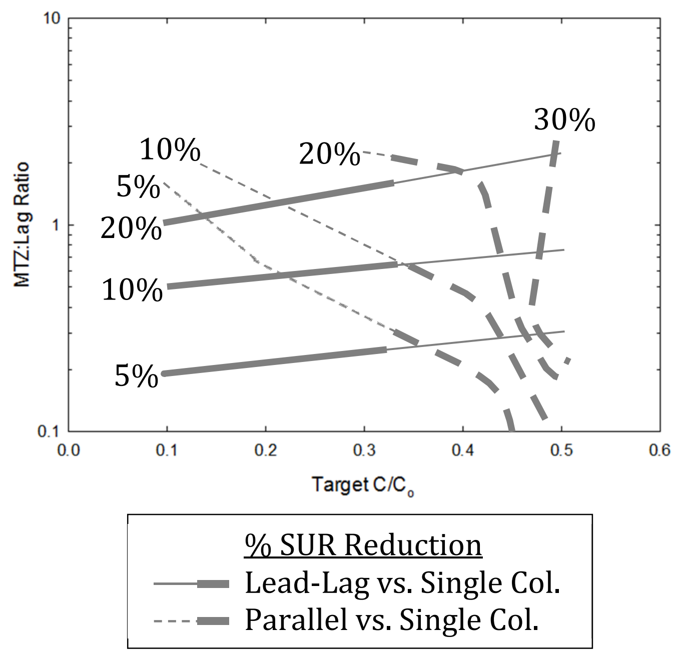

Figure 3.3. Sorbent Usage Rate Reductions Between Lead-Lag and Single Column Arrangements and 2-Column Parallel and Single Column Arrangements for M-3-15 and Mn-0.5-15 GAC Treating Arsenate Contaminated Water
Isopleths of SUR reductions and the lowest SUR configuration option for a given region represented by bold lines

Systems with a long MTZ (higher MTZ:Lag ratio) will achieve significant savings as the MTZ is allowed to pass through two columns in the lead-lag arrangement before the lead column must be replaced, leading nearly all sorbent in the lead column to be saturated before the lag column effluent reaches the treatment objective. The fractional utilization for the lead-lag configurations at a MTZ:Lag ratio of 1.73 are consistently above 0.9, while single column fractional utilization ranges from 0.64 to 0.84 as C/C_o increases from 0.1 to 0.5. Conversely, because of the sharp nature of the MTZ at low MTZ:Lag ratios (e.g., < 0.3), both the single column and lead-lag arrangements will yield a fractional utilization greater than 0.9, leading to minimal SUR reductions when switching to a lead-lag system. With respect to the target effluent C/C_o, the reduction in SUR falls slightly as the treatment objective is raised for a system with a given MTZ:Lag ratio. This trend can be attributed to the higher target C/C_o allowing a column to remain in operation to a higher point on the breakthrough curve, and thus reducing the SUR advantage of lead-lag systems versus single columns.

A comparison between single column and two-column parallel configurations is represented by dashed lines. SUR reductions possible in applying parallel column operation clearly increase as the target C/C_o increases for all MTZ:Lag ratios. This increase is due to the ability of a parallel operation to run columns beyond the target C/C_o. For example, when treating to a target C/C_o of 0.5, this staggering allows each column to remain in operation to a column effluent C/C_o near 1.0 resulting in nearly complete saturation of each column. At low C/C_o values however, only a small gain is achieved by blending effluents from the staggered columns. With respect to MTZ:Lag ratios, trends are less consistent. At C/C_o values less than about 0.45, SUR reductions increase with a rise in MTZ:lag ratio due to the more gradual nature of the MTZ allowing for more blending and greater extension of bed life. Systems treating to relatively high target C/C_o (e.g., 0.5) experience the greatest savings as the MTZ of each column reaches the concave portion at the upper end of the breakthrough curve allowing for significant gains in bed life as C/C_o for each column gradually approaches 1.0. A more detailed explanation of trends in parallel column operation, including discussion of configurations with greater than two columns in parallel, can be found in Denning and Dvorak (2009).

As illustrated in Figure 3.3, lead-lag and parallel configurations offer only relatively small SUR reduction benefits as compared to single columns for cases with lower MTZ:Lag ratios (e.g., < 0.5); fortunately, adding bypass to such systems often offer significant SUR reductions and merit further discussion.

3.3.2. Relationships Between MTZ:Lag, C/C_o, and Bypass

When bypass blending is taken into consideration, the relationships between the MTZ:Lag ratio, target C/C_o, and bypass rate become important in the discussion of column performance (New, 2009). As illustrated in Figure 3.4A-C, the relationships between the MTZ:Lag ratio of a single column system with constant bypass treating to a target C/C_o of 0.3, and three parameters relevant to column performance - bed mass, bed life and SUR - are examined. Each section of Figure 3.4 displays percent reductions in each parameter for both maximum possible and best bypass as compared to a system with 0% bypass. Percent reductions in each figure are based on simulations of M-3-15 modified GAC and Mn-0.5-15 modified GAC treating arsenic contaminated water as an example. In this simulation, the maximum possible bypass was assumed to be 30%, based on a target C/C_o of 0.3, and the best bypass varied between 20% and 30% based on different MTZ:Lag ratio values.

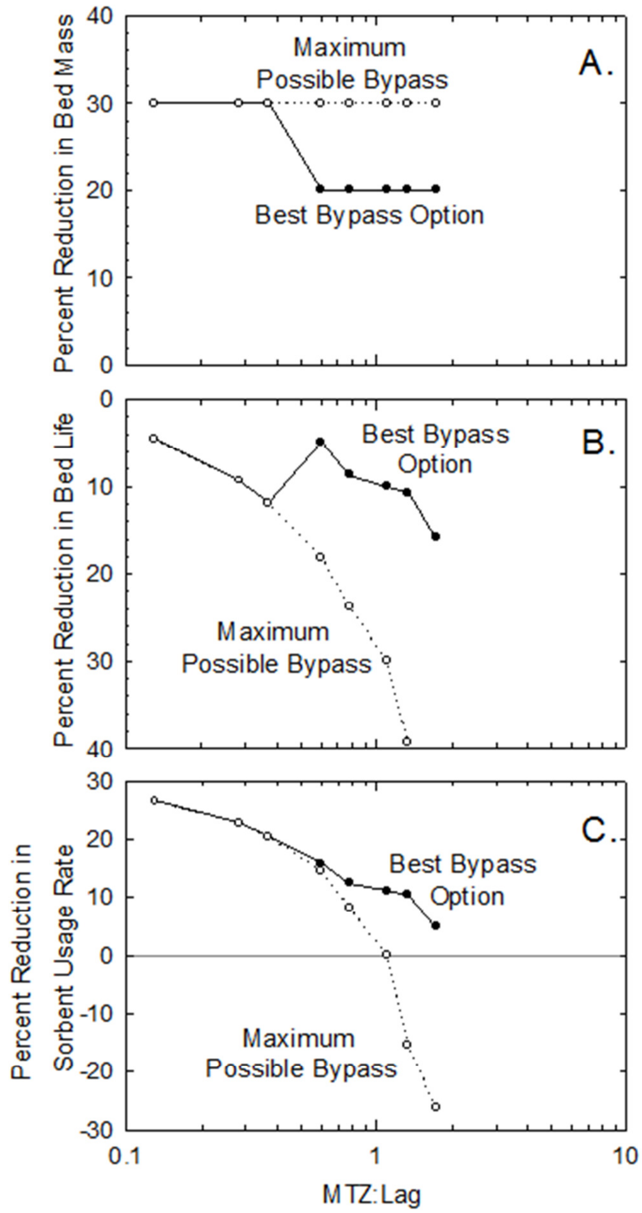

Figure 3.4. Percent Reduction in Bed Mass (A), Bed Life (B), and Sorbent Usage Rate (C) for Single Columns at Best and Maximum Bypass Compared to Single Columns with No Bypass

Reductions for single column arrangements at various MTZ:Lag ratios for both M-3-15 and Mn-05-15 adsorbent when treating to C/C_o of 0.3

Figure 3.4A displays the percent reduction in bed mass for simulated scenarios at a range of MTZ:Lag ratios. For systems operating with a MTZ:Lag ratio below 0.4, the maximum and best bypass are identical, yielding a reduction in bed mass of 30%. With the increase in MTZ:Lag ratio the maximum and best bypass diverged with the best bypass becoming 20%, and accordingly, the reduction in bed mass also decreasing to 20%.

To better illustrate the relationship between bed life loss and SUR reductions, the y-axis of Figure 3.4B has been inverted to place the 0% reduction in bed life at the top and 40% reduction at the bottom. In Figure 3.4B, the maximum and best bypass again diverged at a MTZ:Lag ratio of 0.4, corresponding to a 10% reduction in bed life. Here a reduction in the bed life from 10% to 5% occurs as the best bypass shifts from 30% to 20%. Because reductions in bed life ultimately increase SUR, efforts to minimize the loss in bed life associated with bypass blending will help decrease SUR and improve column performance. Continuance of operation at the best bypass tended to increase the reduction in bed life at higher MTZ:Lag ratios. While both the best and maximum bypass options yield greater reductions in bed life with increasing MTZ:Lag ratios, shifting from the maximum bypass option to the best bypass option (10% less) clearly decreases the reduction in bed life at MTZ:Lag ratios greater than 0.4.

In Figure 3.4B, it is apparent that when the best bypass option becomes 10% less than maximum bypass, the line of percent reduction for the Best Bypass Option is not as smooth as that for the maximum bypass. This discrepancy can be attributed to the fact that the best bypass is determined based on 10% increments. If mathematical optimization was used through the application of smaller increments, yielding the optimum bypass for each scenario, a smoother line would have been produced.

Figure 3.4C shows the same divergence seen in Figures 3.4A and B. Above a MTZ:Lag ratio of 0.4, the best bypass ceases to be the maximum bypass, and the reduction in SUR is no longer the same for maximum and best bypass. Both maximum and best bypass show a continuous decline in percent reduction in SUR for systems with MTZ:Lag ratios higher than 0.4. However, the maximum bypass profile showed a steeper decline. At MTZ:Lag ratios of around 1.0, the percent reduction in SUR approaches zero and continuance with the maximum bypass scenario yields negative percent reductions in SUR. At this point the SUR increases with maximum bypass, making a system without bypass or a lower bypass rate a better option for SUR reductions.

From this discussion it is apparent that with bypass, a portion of the flow does not need to be treated resulting in a lower flow-rate of contaminated water through the column; thus the column size, and accordingly the sorbent mass, can be decreased to maintain the same surface loading rate and EBCT as a column without bypass. However, the reduction in column effluent C/C_o necessary to allow for blending of untreated influent reduce the bed life, leading to an increase in SUR. The following equation was used to calculate SUR and highlights the connection between sorbent mass reduction, bed life reduction, and the overall effect on SUR:

$$SUR\ \left(\frac{mass}{water\ volume}\right) = \frac{Sorbent\ Mass\ (mass)}{Total\ Flow\ Rate\ \left(\frac{water\ vol.}{time}\right) * Column\ Bed\ Life(time)} \tag{3.2}$$

Based on this calculation, it is clear that reductions in bed mass and bed life have conflicting impacts on the SUR. The efforts to balance these factors can be seen in examining systems with differing MTZ:Lag ratios. For example, a system with an MTZ:Lag ratio of 0.13 (farthest left point in the figure) will utilize the maximum bypass (30%), thus reducing bed mass by 30% (Figure 3.4A) which in Equation 3.2 would be represented in the numerator as Sorbent Mass*(1-0.3). The total flow rate through the system remains unchanged and column bed life (Figure 3.4B) would be reduced by 5%, calculated as Column Bed Life*(1-0.05). Combining these factors in Equation 3.2 yields an SUR that 74% of no bypass SUR, or a 26% reduction in SUR (as illustrated in Figure 3.4C). At higher MTZ:Lag ratios, such as 1.1 in Figure 3.4, the best bypass option is no longer the maximum allowable bypass rate. At this point, a 20% reduction in bed mass (Sorbent Mass*(1-0.2)) and a 9% reduction in bed life (Column Bed Life*(1-0.09)) results in an SUR that is 88% of the no bypass SUR, or a 12% net reduction in SUR.

Figure 3.5 expands this relationship between MTZ:Lag ratio, bypass, and bed life further comparing two scenarios of high and low MTZ:Lag profiles, using the same normalized data shown in Figure 3.1. In this case the treatment objective, C/C_o, was assumed to be 0.5 to further demonstrate the differences between profiles at various bypass rates. Bypass values between 0% and 50%, with 10% increments, were examined and the corresponding normalized difference in bed life between the two profiles is displayed. For a single column system with no bypass, no difference in normalized bed life occurs between the two profiles. At the maximum (50%) bypass, the normalized bed life of the gradual profile (MTZ:Lag of 1.33) was 41% shorter than in the case of the steeper profile (MTZ:Lag of 0.13). This conclusion coincides with Figure 3.4B in expressing that higher MTZ:Lag ratios (gradual profiles) will significantly decrease bed life when operated with increased (or maximum) bypass.

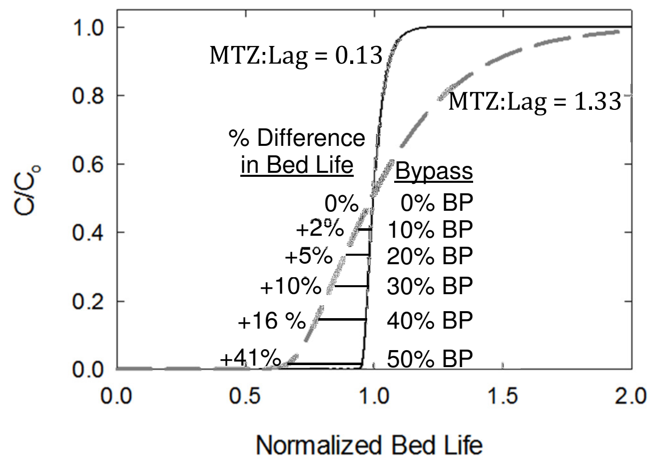

Figure 3.5. Normalized Breakthrough Curves with Lines Indicating Cut-off Points for Varying Levels of By-pass for a Treatment Objective of C/C_o = 0.5
Breakthrough curves for systems using Mn-0.5-15 modified GAC to treat Arsenic contaminated water displayed with the normalized difference in bed-life between MTZ:Lag ratios of 0.13 and 1.33

Bed mass, bed life and SUR reductions are shown in Figure 3.6 at the best bypass rate for a single column when treating to a range of target C/C_o values for systems with low and high MTZ:Lag ratios. The two scenarios presented in Figure 3.6 match those in Figure 3.5. The reduction in bed life for the gradual profile (i.e MTZ:Lag ratio of 1.33) shows a higher slope compared to that of the steeper profile (i.e. MTZ:Lag ratio of 0.13). This can be attributed to the conclusions drawn from Figures 3.4B and 3.5. In both profiles, bed mass reduction rose steadily with the increase in treatment objective and corresponding best bypass (bed mass reductions are equal to the best bypass rate).

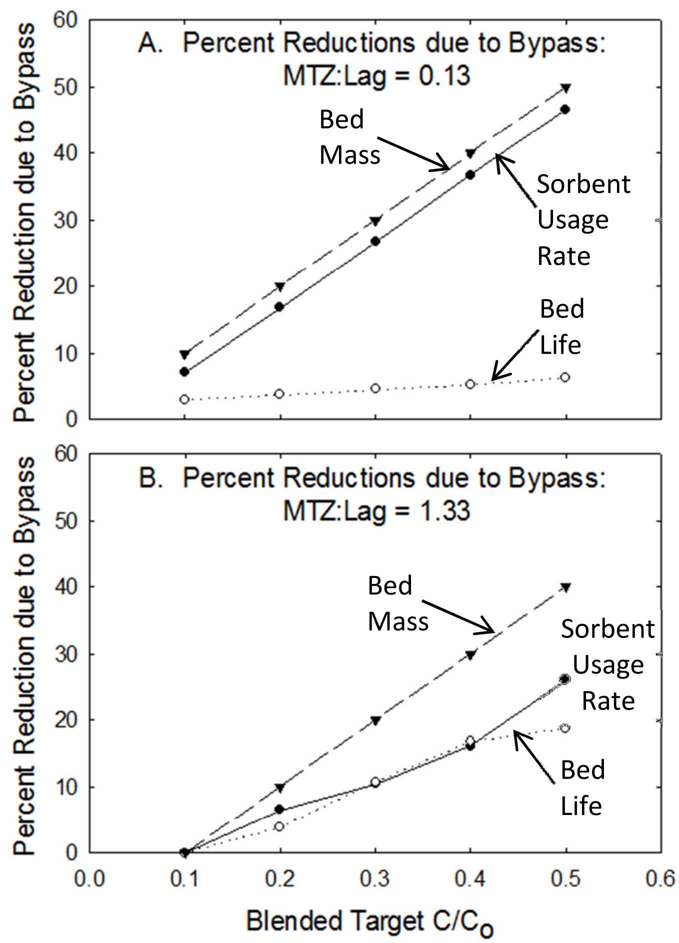

Figure 3.6. Percent Reduction in Bed Mass, Bed Life, and Sorbent Usage Rate due to Bypass for Single Columns at MTZ:Lag of 0.13(A) and 1.33(B) when using Mn-0.5-15 Modified GAC to Treat Arsenic Contaminated Water

3.3.3. Configuration Comparisons and Decision Framework: Bypass Blending

From the above discussion, it can be concluded that MTZ:Lag ratio and the normalized target effluent (C/C_o) can be used to create a decision framework to assist engineers and practitioners in considering the effect of different bypass options and column configurations on the SUR. The reduction in SUR from the addition of bypass to single columns (Figure 3.7) and lead-lag systems (Figure 3.8) are presented here. In both figures, the x-axis represents the normalized effluent concentration and the y-axis represents single column MTZ:Lag ratios. In developing these figures, the three different sorbent-sorbate pairs presented in Table 3.1 were used to allow for evaluation of a spectrum of different possible scenarios. Each scenario was modeled at a range of normalized effluent target concentrations to determine the corresponding best bypass values and aimed to find the reduction in SUR as compared to a no bypass configuration.

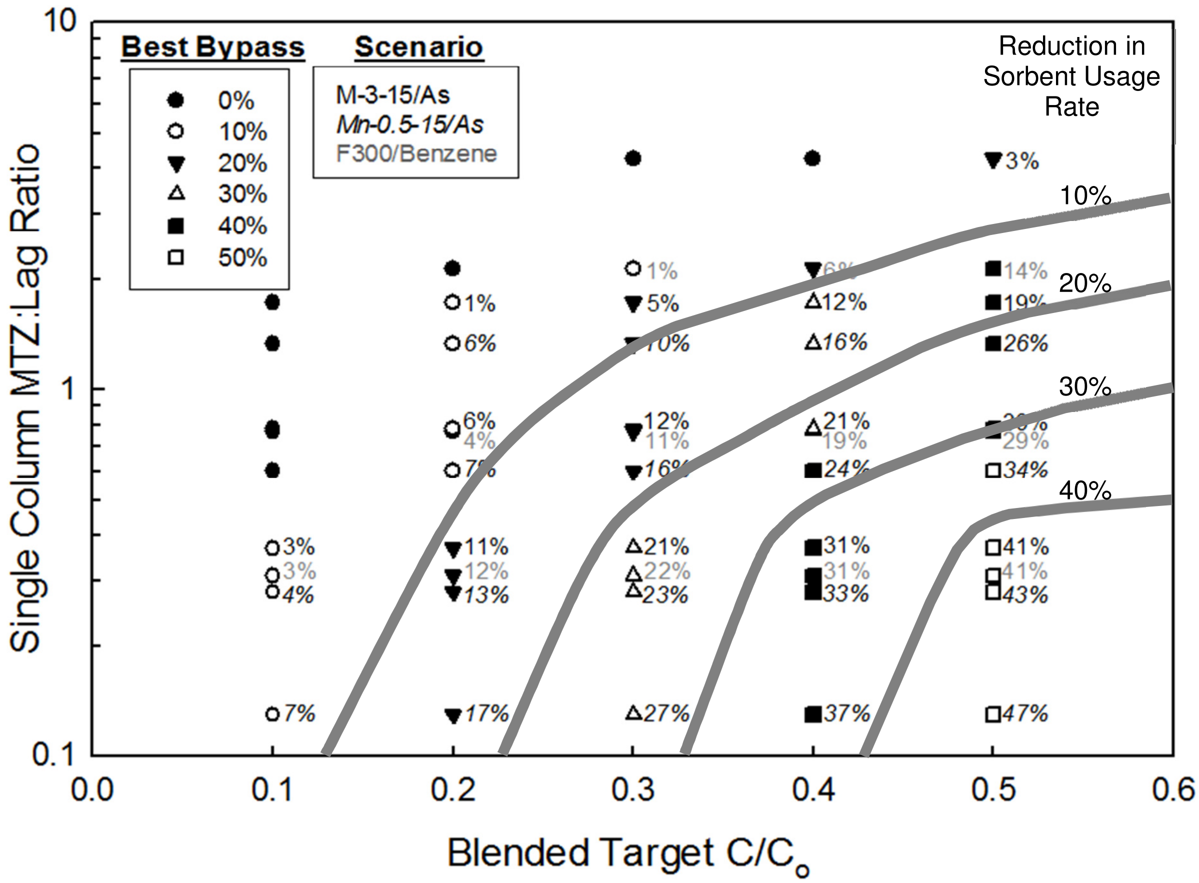

Figure 3.7. Sorbent Usage Rate Reductions Comparing Single Columns with Best and No Bypass

Percent reduction in sorbent usage rates for the three scenarios modeled – M-3-15 GAC treating Arsenate, Mn-0.5-15 treating Arsenate, and F300 GAC treating Benzene – comparing the best bypass option versus no bypass

Accordingly, the numbers presented on the Figures 3.7 and 3.8 represent the reductions in SUR between the no bypass and best bypass options at different treatment objectives and MTZ:Lag ratios, with the best bypass option represented by the symbols listed in the legend. The values presented on the graphs allowed for plotting of isopleths, defining zones of reductions in SUR with 10% increments.

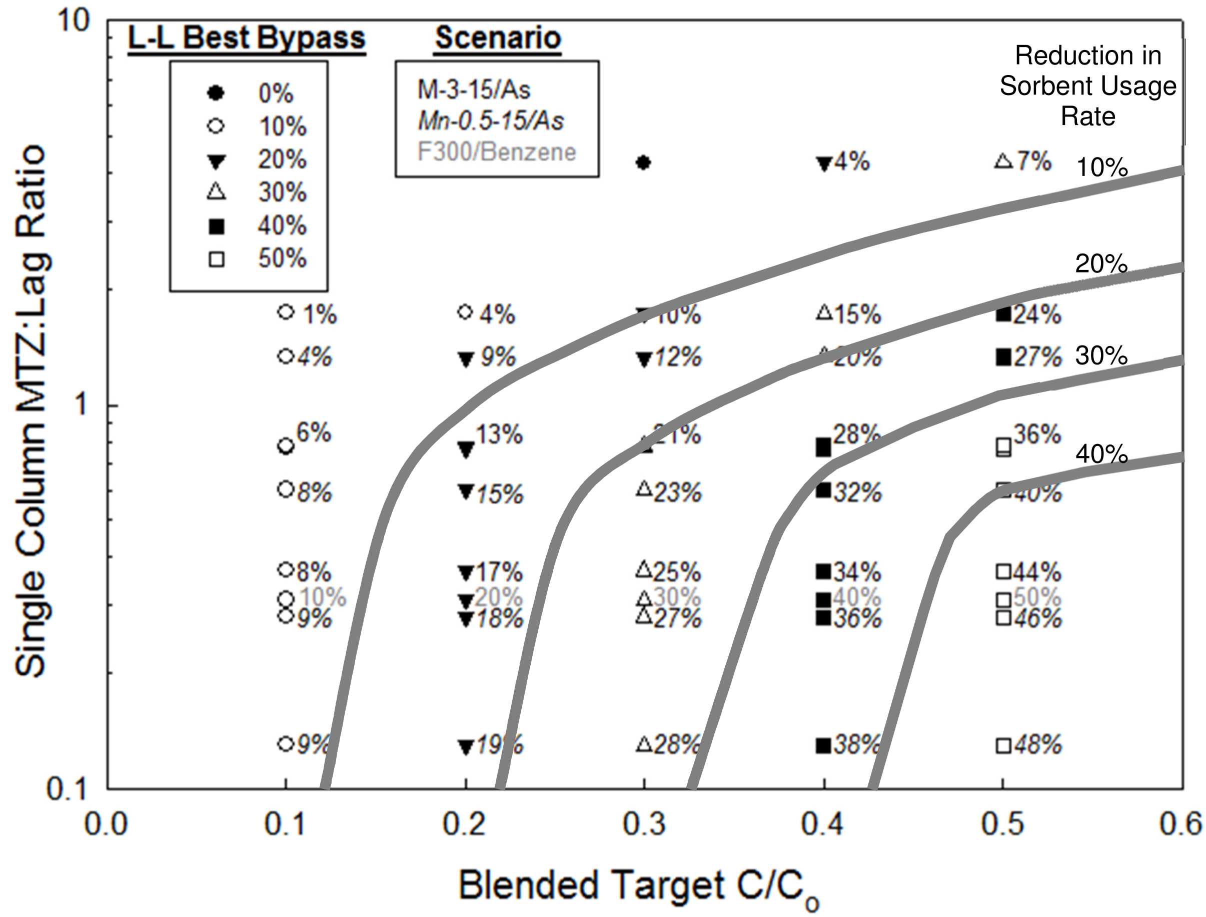

Figure 3.8. Sorbent Usage Rate Reductions Comparing Lead-Lag with Best and No Bypass

Percent reduction in sorbent usage rates for the two scenarios modeled – M-3-15 GAC treating Arsenate, and Mn-0.5-15 treating Arsenate – comparing the best bypass option versus no bypass

It is apparent from both figures that regardless of sorbent-sorbate pairs, for a given approximate MTZ:lag ratio and specific target effluent concentration, these three scenarios nearly coincide with a minimal variation of less than 3%, which can be attributed to slight differences in the MTZ slope, rounding errors in the model, and the impact of simulating and determining best bypass in 10% increments for each scenario (e.g., 0%, 10%, 20%, etc.). For example, in Figure 3.7 for a single column operating at a target effluent concentration of 0.3 and MTZ:Lag ratio of approximately 0.3 the best bypass ratio was found to be 30% with a reduction in SUR in the range of 21% to 23% when compared to a single column with no by pass. This similarity in SUR reduction for the three sorbent-sorbate pairs suggests that utilizing MTZ:Lag ratio and normalized effluent concentration are useful normalization tools for prediction and comparison of column operations.

For both single and lead-lag column configurations, at a specific target effluent concentration, decreasing the MTZ:Lag ratio will result in an increase in the best bypass and a significant reduction in SUR compared to the no bypass option. For example, in Figure 3.8, using a lead-lag configuration at a normalized target effluent concentration of 0.5 and operating at a high MTZ:Lag ratio of approximately 4.0, the best bypass option was 30% of the flow (versus 50% for the maximum possible bypass) and resulted in a SUR reduction of 7% compared to lead-lag with no bypass. For a MTZ:Lag ratio of 0.6 at a C/C_o of 0.5, the best bypass increased to 50% and the reduction in SUR reached 40%. These trends are consistent with those presented in Figure 3.4.

Furthermore, at a specific MTZ:Lag ratio, increasing the normalized target effluent concentration corresponds to a rise in the best bypass ratio and an improvement in SUR. For instance, in Figure 3.7 it is evident that for a single column operating at an MTZ:Lag ratio of 0.3, as the normalized treatment objective is raised, the best bypass increases from 10% to 50% as C/C_o shifts from 0.1 to 0.5; accordingly the SUR is reduced by about 35%. Again this sequence follows that shown in Figure 3.6.

Comparing Figures 3.7 and 3.8, it is apparent that adding bypass to a lead-lag configuration enhances SUR performance at higher MTZ:Lag ratios (esp. > 0.5), which makes the use of lead-lag configuration with bypass beneficial. The MTZ:Lag ratios for the lead-lag bypass comparison in Figure 3.8 are based on the MTZ:Lag of the lead column, treated as a single column. Because the longer MTZ is allowed to pass through both the lead and lag column before the lead column is replaced, the extended bed life and high fractional utilization, allows bypass to remain a viable option to higher MTZ:Lag ratios and the lead-lag arrangement will yield a lower SUR. However, complexity in operation and required installations should also be considered when evaluating shifting from a single column to the lead-lag configuration. These considerations are beyond the scope of this paper.

The results shown in Figure 3.7 of where the maximum bypass results in the lowest SUR and where a lower bypass rate is best, are consistent with system case studies published by Severn Trent Services (2010a, 2010b, and 2010c). For example, Severn Trent Services utilized a bypass rate equal to the target effluent C/C_o to two independently operated columns of sorbent to treat arsenic contaminated water to a target C/C_o of 0.2 with a 20% bypass of untreated influent at Twentynine Palms, California (Severn Trent Services, 2010b). In another example, Severn Trent Services applied a bypass rate less than the maximum in the town of Perkasie, Pennsylvania, as a 32% bypass of untreated influent allowed the system to maintain a C/C_o between 0.67 and 0.75 (Severn Trent Services, 2010c)

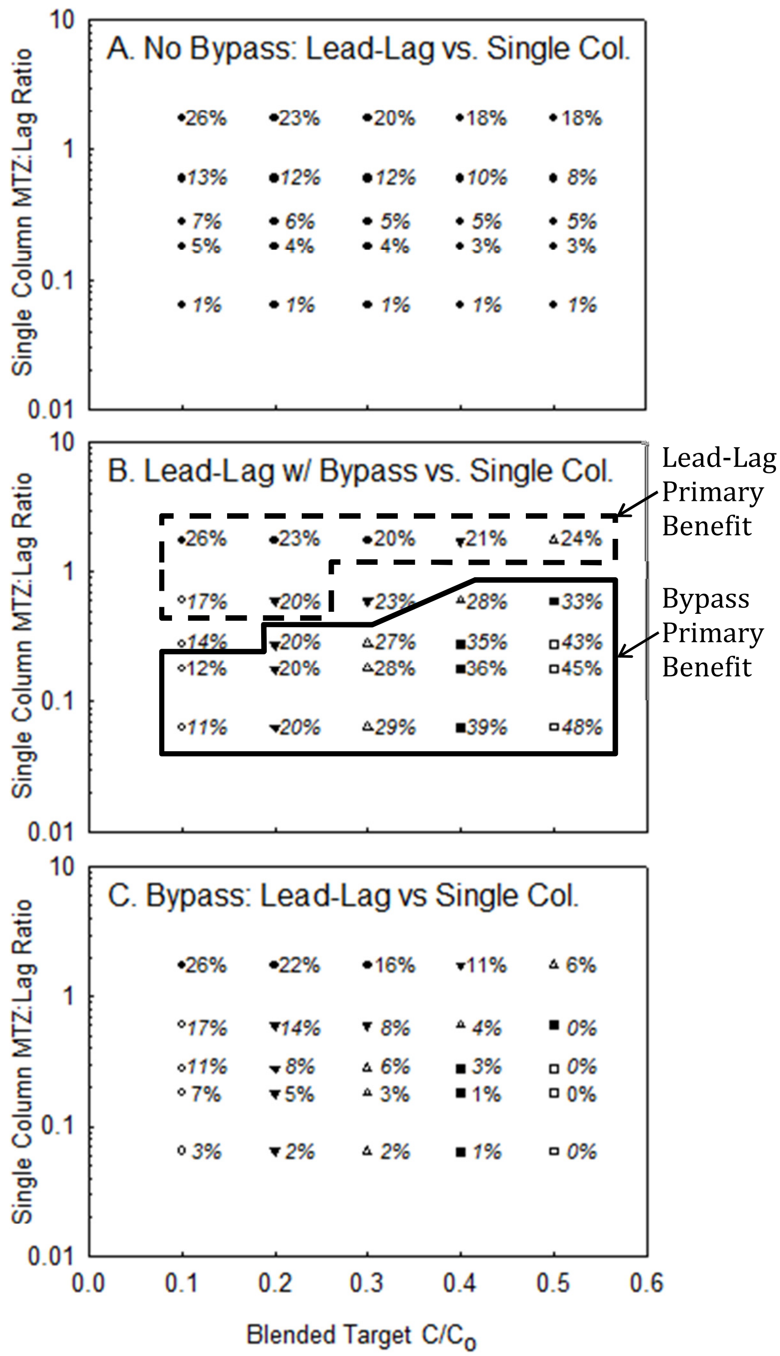

Figure 3.9. Sorbent Usage Rate Reductions Between Lead-Lag and Single Column Arrangements for M-3-15 and Mn-0.5-15 GAC Treating Arsenate Contaminated Water

Comparing lead-lag no bypass versus single column no bypass (A), lead-lag best bypass versus single column no bypass (B), and lead-lag best bypass versus single column best (C)

After comparing the SUR benefit of applying bypass blending for a particular column configuration, it is important to compare sorbent usage with the use of bypass for various configurations. Frequently engineers, utility managers, and regulators must consider the advantages and disadvantages of several multiple column configurations for sorption systems. In Figures 3.9A-C, simulations to develop the comparisons between column configurations at each MTZ:Lag ratio were based on two columns of identical size arranged as single columns, or lead-lag series. When comparing the different arrangement options an important distinction must be made. Because flow rates through a system cannot necessarily be changed, different arrangements will send varying flow rates to each column. Thus, the two independently operated single columns will each treat half the flow in each column as the columns are essentially arranged in parallel, but operated independently. Lead-lag arrangements, however, will pass the entire flow through both columns. This difference in flow rate ultimately alters the MTZ:Lag ratio due to a change in EBCT. In Figure 3.9A-C, points were placed at the single column MTZ:Lag value for the sake of comparison.

Similar to Figures 3.7 and 3.8, Figure 3.9 illustrates several comparisons of different column configurations. While the SUR improvements associated with bypass blending for a particular arrangement were the focus of comparisons in Figures 3.7 and 3.8, comparing SUR for single column and lead-lag configurations, both with and without bypass, are the focus of sections A-C in Figure 3.9. As in Figures 3.7 and 3.8, the best bypass rate is represented by the same symbols at each target C/C_o and MTZ:lag ratio modeled. Percent reductions in SUR are indicated by numbers and placed at each point.

Like Figure 3.3A, Figure 3.9A presents the percent reductions in SUR when comparing a single column operation to a lead-lag series arrangement, neither incorporating bypass. Figure 3.9A replaces the isopleths in Figure 3.3A with numerical savings at each point to provide a baseline for understanding the subsequent comparisons and relationships.

Figure 3.9B compares lead-lag with bypass to single columns without bypass, displaying the potential SUR reductions at each point modeled. Trends in SUR reduction illustrated in Figure 3.9B are somewhat similar to those depicted in Figures 3.7 and 3.8. As the MTZ:Lag ratio increases, best bypass rates for the lead-lag system are decreased. At high C/C_o values, the potential SUR reduction falls as the bypass rate is decreased. Conversely, at low target C/Co values, SUR reductions continue to increase at higher MTZ:Lag ratios as the lead-lag configuration is the dominant factor contributing to savings in SUR. At low MTZ:Lag values, as the treatment objective and corresponding best bypass is raised, SUR reduction increases. Savings displayed in Figure 3.9B, however, are greater than those presented in Figures 3.7 and 3.8 as the change from a single column without bypass to a lead-lag system utilizing the best bypass option incorporates the benefit of reduced bed mass associated with bypass blending discussed in Figures 3.3, 3.7 and 3.8, and the extended bed life made possible by the lead-lag system, as discussed with Figures 3.3A and 3.9A. Regions of Figure 3.9B have been highlighted to illustrate where the lead-lag configuration (dashed line) or bypass blending (solid line) are the largest factor contributing to the reduction in SUR. Ultimately, the change from a single column without bypass to a lead-lag system incorporating the best bypass option leads to significant SUR reductions at all MTZ:Lag ratios and target C/C_o values depicted.

A recent case study outlined the benefits of applying bypass to sorption systems. Arizona American Water addressed the need for arsenic removal and improved efficiency in each of the four granular iron media adsorption plants by implementing both a lead-lag configuration and bypass blending in four treatment plants (Mecham, 2010). When bypass was implemented in each of the four treatment facilities, savings realized closely followed the results presented in Figure 3.9B when compared to single columns without bypass. Table 3.2 presents the treatment objective, approximate MTZ:Lag ratio, and realized savings for the four treatment plants. The final row shows a comparison of the predicted savings developed in this study (shown in Figure 3.9B) to those of Mecham (2010) and indicates the data closely follows that predicted by this study.

Table 3.2. Arizona American Water Case Study Results (from Mecham, 2010) and Modeling Heuristics

	Agua Fria Plant 1	Agua Fria Plant 2	Agua Fria Plant 5	Sun City West Plant 2
Target C/C_o	0.29 – 0.57	0.5 – 1.0	0.10 – 0.8	0.32 – 0.8
Approximate MTZ:Lag	0.60	0.60	0.60	0.60
Reported Reduction in Sorbent Usage vs. Single Col.	40%	46%	60%	57%
Heuristic Reduction in Sorbent Usage (Figure 3.9B)	23% to 33%	>33%	17% to >33%	23% to >33%

Finally, Figure 3.9C introduces a single column operated with the best bypass option to the comparison, examining the potential SUR reduction from a lead-lag versus a single column arrangement, both utilizing the best bypass option. Trends in SUR reductions in Figure 3.9C more closely resemble those in Figure 3.9A. For the majority of situations modeled and depicted here, the best bypass rates were the same for both single column and lead-lag systems. Therefore, where best bypass is identical, improvements in SUR can be primarily attributed to the extended bed life made possible by a lead-lag system. However, where the best bypass options vary, differences arise. Symbols in Figure 3.9C represent the best bypass option for the lead-lag system. To compare best bypass options for the two configurations, refer to Figure 3.7 for the single column best bypass rates. For example, at an MTZ:Lag ratio of 1.73 and target C/C_o of 0.5, a single column can utilize 40% bypass while best bypass for a lead-lag system is 30%. Therefore, the reduction in SUR between the lead-lag and single column system fell from 18% in Figure 3.9A to 6% in Figure 3.9C. Again, when comparing these systems, complexities in operation and necessary installations should be taken into consideration, but were outside the scope of this study.

3.3.4. Configuration Comparisons

The results from this study can be summarized on a pair of figures to illustrate the regions on the MTZ:Lag vs. C/C_o plot where each configuration may provide the lowest SUR. Figure 3.10A presents a comparison of lead-lag, both with and without bypass, single columns without bypass, and parallel column configurations without bypass. In some cases, the complexity of the operation of a lead-lag system with bypass may be undesirable, so Figure 3.10B was developed to present a similar comparison of single columns, both with and without bypass, lead-lag without bypass, and parallel column configurations.

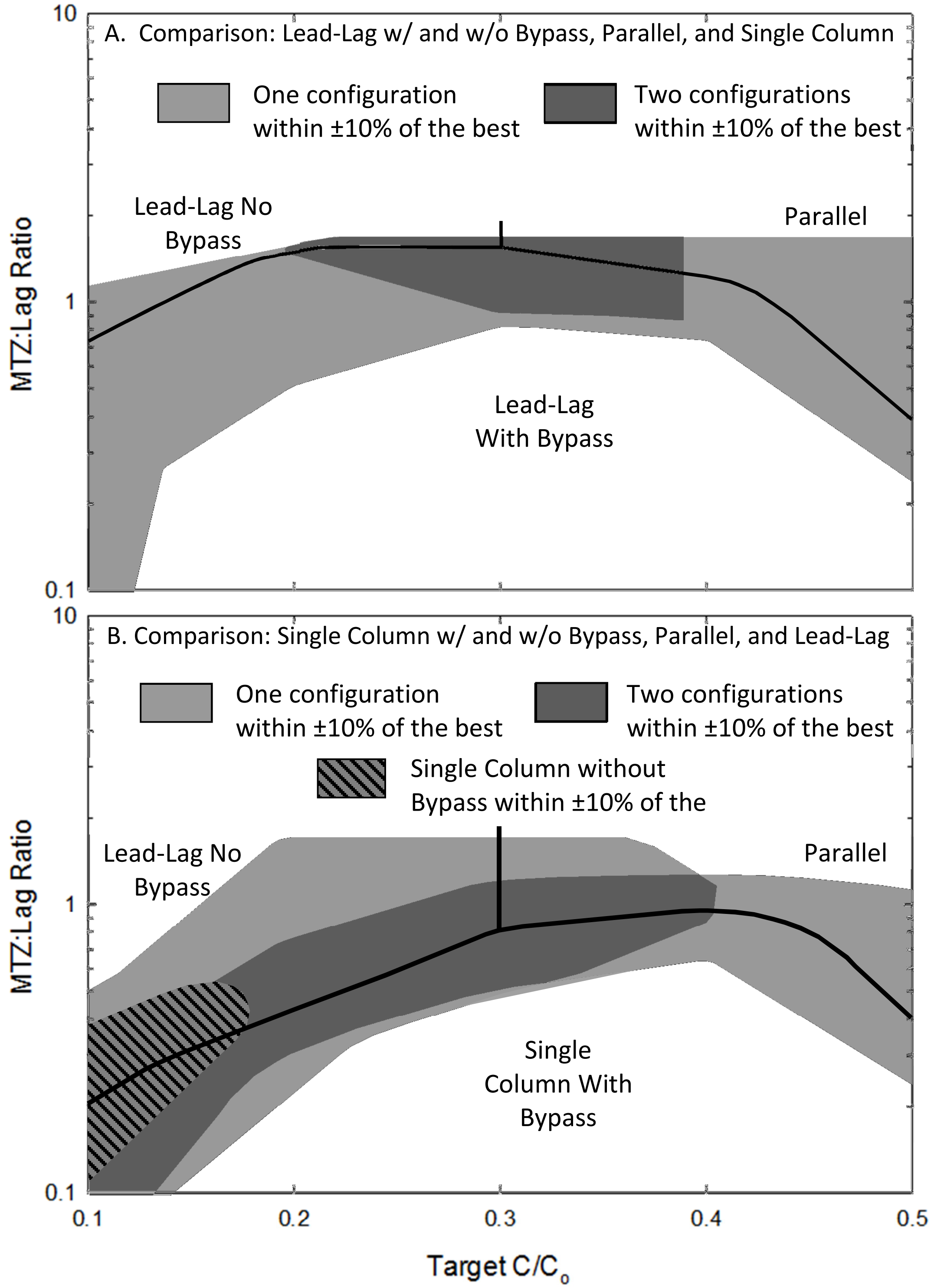

Figure 3.10. Regions of Lowest Sorbent Usage Rate Configuration:
Single Column No Bypass, Lead-Lag No Bypass, Lead-Lag Best Bypass, and Parallel (A), and Single Column No Bypass, Single Column Best Bypass, Lead-Lag No Bypass, and Parallel (B)

The light gray regions on Figure 3.10 represent where the SUR for two configurations are within 10%; a darker gray shade indicates three configurations within 10%; the hatched region indicates four configurations (which include single columns without bypass) within 10% of the lowest SUR option.

Figures 3.10A and B contain three primary regions. At relatively low MTZ:Lag ratios (e.g., < 0.1) and a breadth of C/C_o values, bypass (either with lead-lag or single column operation) will clearly yield the lowest SUR option. As discussed with Figures 3.8 and 3.9, this low SUR can be attributed to the use of the maximum possible bypass rate, thus reducing the column size. A small region of lower C/C_o values (e.g., < 0.3) and high MTZ:Lag ratios find lead-lag without bypass to be the best configuration option, consistent with Figures 3.9A and B. Although bypass is not beneficial in this region, the long MTZ is allowed to pass through both columns before the lead column must be replaced, thus reducing SUR. Finally, parallel columns yield the lowest SUR at higher MTZ:lag ratios and C/C_o values greater than about 0.3. When operating a system with a more gradual MTZ (higher MTZ:Lag ratio) and higher treatment objective, greater reductions in SUR are possible as more blending is allowed between the two columns with staggered MTZs. For example, when treating to a target C/C_o of 0.5, the first column can remain in operation as its effluent concentration goes well above the treatment objective, nearing $C/C_o = 1.0$, because blending allows the low column effluent concentration of the second column to offset the higher concentration of the first column. While constant bypass is not beneficial in this region, a variable bypass system may be viable and could yield considerable reductions in SUR, similar to those experienced with parallel columns. Variable bypass allows for gradually reducing the bypass flow rate as the MTZ reaches the end of the column and the effluent concentration beings to rise. Such a system may have the potential to offer sorbent usage savings in situations when constant bypass is unfeasible (New, 2009).

Due to the potential design and operation complexities associated with a lead-lag system with bypass. Figure 3.10B replaces lead-lag with bypass by single columns with bypass. While Figures 3.10A and B have very similar regions, in Figure 3.10B lead-lag without bypass yields the lowest SUR for a larger range of MTZ:Lag ratios because lead-lag with bypass (Figure 3.10A) has been replaced with single column with bypass (Figure 3.10B). As discussed previously, the reduction in bed life that occurs at higher MTZ:Lag ratios when using single columns with bypass will limit the potential for savings with the use of bypass. Thus, lead-lag without bypass is the lowest SUR option at low C/C_o values, and at higher MTZ:Lag ratios. Parallel configurations remain the best option at high MTZ:Lag ratios and C/C_o values greater than 0.3. Although parallel columns without bypass do not perform better than the other options, parallel without bypass remains competitive with lead-lag without bypass and single columns with bypass along the boundary line of the regions for the other two options (area shaded in darker gray). Finally, at a region of low C/C_o values and low MTZ:Lag ratios, SUR for single columns without bypass are within 10% of the other configuration options (area shaded in hatched black).

Some common conventions in environmental engineering practice can be related to Figures 3.10A and B. First, a common convention for the treatment of disinfection byproduct precursors (DBPs) and total organic carbon is to apply parallel columns to minimize the sorbent usage rate (e.g., Clark and Lykins, 1989). Target C/C_o (>0.3) and

MTZ:lag (>0.6), in DBP and total organic carbon removal with sorbents such as granular activated carbon, are both typically relatively high (e.g., Dvorak and Maher, 1999; McGuire et al., 2002). This convention from the literature is consistent with Figures 3.10A and B where parallel columns generally offer low or lowest SUR.

Additionally, ion exchange systems for municipal water softening are frequently characterized by low MTZ:Lag ratios (e.g., < 0.2) and target C/C_o values of 0.25 or greater, and are designed to operate as independent single columns with bypass (e.g., Hamel, 2011; Stevenson, 1997). Consistent with the data in Figures 3.7, and 3.10B there is a large potential benefit in sorbent usage possible when including a bypass line in a single column configuration and only a small incremental benefit for applying lead-lag with bypass.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

A conceptual framework to evaluate sorbent usage rate of single columns with and without bypass, lead-lag series with and without bypass, and parallel columns without bypass was developed. The framework is based on several assumptions, including single component, constant pattern, and s-shaped breakthrough curves. Although these conditions do not apply to all applications in the field of engineering, the diagrams presented here are useful in illustrating the trends with changing parameters. From this research, the following conclusions were made:

- Normalization of breakthrough curves as MTZ:Lag were confirmed to be an effective parameter in allowing for comparison of different systems and configurations and is consistent with examples from scenarios in practice.
- Comparing single column and lead-lag arrangements without bypass showed that using a lead-lag arrangement led to more significant savings at high MTZ:Lag ratios (Figure 3.3A and3. 9A). In addition, bed life increase can be attributed to the fact that the long MTZ is allowed to pass through two columns in series before replacing the lead column, thus reducing SUR.
- Parallel column configurations without bypass have an advantage in SUR over single column and lead-lag at high target C/C_o, particularly at high MTZ:Lag ratios. Due to the staggered MTZs between the two parallel columns, longer MTZs allow for greater blending of column effluents and increase in bed life.

- Single column systems with bypass blending allowed for considerable savings in sorbent usage, particularly at low MTZ:Lag ratios and moderate to high blended target C/C_o values (Figure 3.7).
- Trends in SUR reductions for lead-lag systems with bypass blending (Figure 3.8) were very similar to single columns with bypass (Figure 3.7). However, due to the extension in bed life possible in the series arrangement of lead-lag configurations, maximum bypass remains the best bypass option to higher MTZ:Lag ratios and savings decrease more slowly with an increase in MTZ:Lag.
- SUR reductions between lead-lag systems utilizing best bypass and a single column with no bypass (Figure 3.9B) follow trends similar to those in Figures 3.7 and 3.8. Again, as the column size is reduced with the use of bypass, the savings are increased. These savings again decrease as the MTZ:Lag rises and the bed life is shortened.
- A comparison of single column and lead-lag systems, both utilizing the best bypass options for each point (Figure 3.9C), reveals trends relatively similar to those in Figures 3.3A and 3.9A. Because bypass rates and corresponding column sizes at each point are similar for the two systems, the primary factor in reducing SUR is the lead-lag arrangement. Thus, savings are similar to those in comparing single column and lead-lag arrangements with no bypass.
- Similar to parallel columns, variable bypass systems offer additional savings at high MTZ:Lag ratios. As the flow rate of untreated water around the column is reduced while the column effluent concentration rises, the gradual tapering of effluent blending allows for greater bed life over other systems (New, 2009).

4.2. Recommendations for Further Research

The findings presented here could be further expanded and application to real-world situations could be made stronger by investigating the following recommendations for future research:

- While this study focused on the impact of blending with a constant bypass system, it is likely variable bypass can provide additional savings over the configurations discussed here and it is worth further investigation to better identify what the impact of such a system might be on sorbent usage rate.
- Modeling in this study assumed a single contaminant system. In real-world applications of adsorption systems this is rarely the case. Therefore, the impact of multiple contaminant competition on sorbent usage rate for the various configurations studied would be beneficial to practicing engineers.
- To ensure a system does not violate a particular effluent concentration, operators of sorption facilities often monitor and remove columns before the treatment objective is fully met. This strategy involves implementing a safety factor to the maximum allowable concentration, reducing the cut-off point for the system. The practice of implementing a safety factor aims to avoid allowing excess contaminant to reach the effluent. Different methods of reducing the target concentration may impact sorbent usage and efficiency of a sorption system. Thus, investigation into the effect various methods of applying safety factors would improve the applicability of these findings to actual operation of such systems.

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Appendix A. Procedures for Configuration Simulations

A breakdown of relevant calculations and a detailed procedure for simulating the different column configuration options can be found in the Appendices of New (2009). These procedures were largely followed for simulations performed in this study. Minor modifications were needed and are discussed in Table A.1.

Table A.1. Procedures Utilized in Simulations of Various Column Configurations

	Reference	Pages	Alterations/Additions
Single Column and Bypass Calculations	Appendix B, New (2009)	77 - 79	None
Single Column with Constant Bypass Procedure	Appendix F, New (2009)	86 - 87	None
Lead-Lag Procedure	Appendix G, New (2009)	88 - 92	To adapt the spreadsheet used by New (2009) for Scenarios A and B, an extra column was included to convert the C/C_o to an actual mg/L concentration. Because the initial influent concentration of arsenic was 0.025 mg/L, the normalized C/C_o was multiplied by 0.025 mg/L to convert the lead-column effluent to mg/L for a concentration that could be used as the influent to the lag column.
Parallel Procedure	Appendix H, New (2009)	93 - 95	None
Lead-Lag with Constant Bypass Procedure	Appendix J, New (2009)	98 - 100	The same conversion discussed above with Appendix G to convert C/C_o to mg/L concentration was also used in simulations with bypass.

Appendix B. Contaminant/Sorbent Properties and PSDM Inputs

Table B.1. Contaminant Physical and Chemical Properties

	Contaminant	
	Arsenate	*Benzene*
Applied Scenario(s)	A,B	C
Molecular Weight (mg/mmol)	74.9	78.1
Molar Volume (m^3/kmol)	0.013	0.098
Boiling Point (C)	614	80.1
Initial concentration (mg/L)	0.025	1
Liquid Density (g/mL)	5.78	0.873
Solubility (mg/L)	1.00	1760
Vapor Pressure (mmHg)	7.5×10^{-3}	94.5

Table B.2. Sorbent and Isotherm Data

Scenario	**A**	**B**	**C**
Contaminant	*Arsenate*	*Arsenate*	*Benzene*
Sorbent	M-3-15 Modified GAC	Mn-0.5-15 Modified GAC	Calgon F300 GAC
Freundlich K (mg/g)(L/mg)$^{(1/n)}$	1.01	2.60	16.6
Freundlich 1/n	0.66	0.58	0.39
Film Diffusion (cm/s)	5.50×10^{-3}	6.20×10^{-3}	8.60×10^{-3}
Surface Diffusion (cm^2/s)	4.50×10^{-10}	4.50×10^{-10}	6.24×10^{-40}
Pore Diffusion (cm^2/s)	3.67×10^{-6}	3.67×10^{-6}	7.61×10^{-6}
Tortuosity	1.91	1.91	1.00
Apparent Density (g/mL)	2.0	2.0	0.48
Particle Radius (m)	0.050	0.050	0.082
Porosity	0.78	0.78	0.65
Shape Factor	1.2	1.2	1.0

Appendix C. Column Parameters at Various MTZ:Lag Ratios

The following tables present column parameters from the various simulations performed to determine sorbent usage rates. Column modifications to alter MTZ:Lag ratios and bypass rate are displayed for each scenario.

Table C.1. Scenario A – M-3-15 Modified GAC Treating Arsenate Contaminated Water

% Bypass	Col. Flow	Col. Diam.	Volume (m^3) MTZ:Lag				Mass (kg) MTZ:Lag			
	(m^3/d)	*(m)*	*0.37*	*0.78*	*1.73*	*4.26*	*0.37*	*0.78*	*1.73*	*4.26*
0%	905	2.00	50.3	25.1	12.6	6.3	20,000	10,000	5,000	2,500
10%	814.5	1.90	45.4	22.7	11.3	5.7	18,000	9,000	4,500	2,250
20%	723	1.79	40.3	20.1	10.1	5.0	16,000	8,000	4,000	2,000
30%	632.5	1.67	35.0	17.5	8.8	4.4	14,000	7,000	3,500	1,750
40%	542	1.54	29.8	14.9	7.5	3.7	12,000	6,000	3,000	1,500
50%	451.5	1.41	25.0	12.5	6.2	3.1	10,000	5,000	2,500	1,250

Table C.2. Scenario B – Mn-0.5-15 Modified GAC Treating Arsenate Contaminated Water

% Bypass	Col. Flow	Col. Diam.	Volume (m^3) MTZ:Lag				Mass (kg) MTZ:Lag			
	(m^3/d)	*(m)*	*0.13*	*0.28*	*0.60*	*1.33*	*0.13*	*0.28*	*0.60*	*1.33*
0%	905	2.00	50.3	25.1	12.6	6.3	20,000	10,000	5,000	2,500
10%	814.5	1.90	45.4	22.7	11.3	5.7	18,000	9,000	4,500	2,250
20%	723	1.79	40.3	20.1	10.1	5.0	16,000	8,000	4,000	2,000
30%	632.5	1.67	35.0	17.5	8.8	4.4	14,000	7,000	3,500	1,750
40%	542	1.54	29.8	14.9	7.5	3.7	12,000	6,000	3,000	1,500
50%	451.5	1.41	25.0	12.5	6.2	3.1	10,000	5,000	2,500	1,250

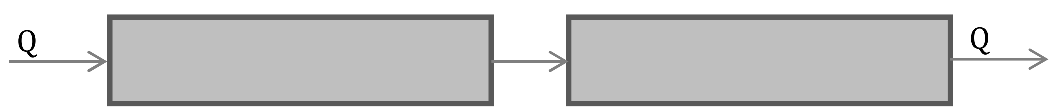
Table C.3. Scenario C – Calgon F300 GAC Treating Benzene Contaminated Water

% Bypass	Col. Flow	Col. Diam.	Volume (m^3) MTZ:Lag			Mass (kg) MTZ:Lag		
	(m^3/d)	*(m)*	*0.31*	*0.77*	*2.13*	*0.31*	*0.77*	*2.13*
0%	2142	3.05	44.7	20.9	10.1	20,557	9,593	4,625
10%	1928	2.89	40.1	18.8	9.1	18,501	8,634	4,163
20%	1714	2.73	35.8	16.7	8.1	16,446	7,675	3,700
30%	1499	2.55	31.3	14.6	7.0	14,390	6,715	3,238
40%	1285	2.36	26.8	12.5	6.0	12,334	5,756	2,775
50%	1071	2.16	22.4	10.5	5.1	10,279	4,797	2,313

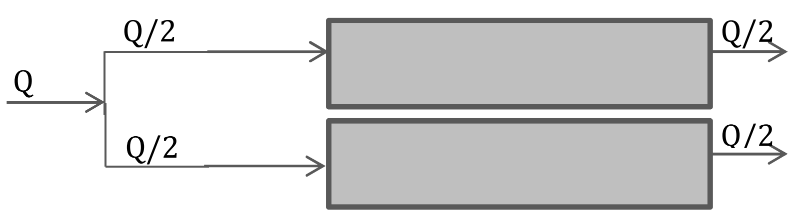
Appendix D. Flow Rate Adjustments for Single Column and Lead-Lag Comparisons

To compare Lead-Lag and Single Column arrangements, one must consider the scenario where a treatment plant has two columns and must decide whether to operate the two columns as a lead-lag series arrangement or as two independent single columns. This consideration becomes important when examining the flow to each column. Because a plant is likely faced with a flow rate that cannot be altered and may already possess two columns of a given size, a difference in flow to each column arises. The following figures illustrate this difference:

Lead-Lag



Single Column



Because each column in a single column arrangement receives half the total flow rate, the velocity of water through the column is halved, and as a result, the MTZ:Lag ratio is altered. This means the MTZ:Lag ratio is reduced as if the column length were doubled . For example, a system treating the full flow rate, Q, using Mn-0.5-15 GAC to treat Arsenate with a MTZ:Lag ratio of 1.33, will produce a MTZ:Lag ratio of 0.60 when treating half the flow rate, or Q/2. This makes sense intuitively as the EBCT is the primary factor in altering the MTZ:Lag ratio within a given scenario. To increase and decrease the MTZ:Lag ratio during simulations, the column length was reduced or increased, respectively, to alter the EBCT.

<u>Sorbent Usage Rate</u>

In simulations for a given system (e.g. single column or lead-lag) the flow rate to a column remained constant while the bed length, and concurrently bed-mass, was doubled or halved to reduce or increase the MTZ:Lag ratio, respectively. When comparing single columns to lead-lag systems, by maintaining a constant bed length and bed mass, and reducing the flow rate by half for single column arrangements, the change in MTZ:Lag ratio discussed above occured. This is most easily related to sorbent usage rate (SUR) by examining the equation used to calculate SUR:

$$S.U.R. = \frac{Bed\ Mass\ (kg)}{Flow\ Rate\ \left(\frac{m^3}{d}\right) * Bed\ Life(d)}$$

In simulations comparing one system with bypass to the system without bypass (e.g. lead-lag) the bed length and bed mass were doubled to reduce MTZ:Lag. As a result bed life was changed and flow rate remained consistent. In comparisons between systems, maintaining a consistent bed mass and halving the flow rate had the same effect on the S.U.R. calculation. The following table displays each of these factors from actual simulations:

Table D.1. Alterations to Columns when Evaluating a Particular Configuration
(Bed Length Change)

	MTZ:Lag	Flow Rate	Bed Mass	Bed Length	Velocity	EBCT	Bed Life (to C/C_o 0.5)	Sorbent Usage Rate (to C/C_o 0.5)
		(m^3/d)	(kg)	(m)	(m/hr)	(min)	(d)	(kg/m^3)
	1.33	905	2500	2	12	10	31.7	0.087143
	0.6	905	5000	4	12	20	65.3	0.084607

Table D.2. Alterations to Flow when Comparing Single and Lead-Lag Configurations
(Flow Rate Change)

	MTZ:Lag	Flow Rate	Bed Mass	Bed Length	Velocity	EBCT	Bed Life (to C/C_o 0.5)	Sorbent Usage Rate (to C/C_o 0.5)
		(m^3/d)	(kg)	(m)	(m/hr)	(min)	(d)	(kg/m^3)
L-L	1.33	905	2500	2	12	10	31.7	0.087143
S.C.	0.6	452.5	2500	2	6	20	65.3	0.084607

In Figures 3.7 and 3.8, changes in MTZ:Lag were achieved by altering the columns as shown in Table D.1.

Figures 3.3 and 3.9 examine comparisons of column performance between lead-lag and single column configurations. These figures have points placed at the single column MTZ:Lag ratio. Reviewing table D.2, this means that percent difference in SUR for a point placed at an MTZ:Lag ratio of 0.6 on the y-axis is comparing a lead-lag configuration with a MTZ:Lag ratio of 1.33 to a single column configuration with a MTZ:Lag ratio of 0.6.

Appendix E. Sorbent Usage Rate Data: Single Column Bypass Comparison

Tables displayed here present sorbent usage rate data for single column arrangements with 0-50% bypass at a range of MTZ:Lag ratios. Usage rate data was compiled simulating each scenario at every potential bypass rate for a given treatment objective (C/C_o). This data was used in developing Figures 3.7 and 3.9.

Scenario A – M-3-15 Modified GAC Treating Arsenate Contaminated Water

MTZ:Lag = 0.37

	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.316	0.307	NA	NA	NA	NA
0.2	0.307	0.283	0.272	NA	NA	NA
0.3	0.300	0.275	0.251	0.238	NA	NA
0.4	0.294	0.268	0.243	0.219	0.204	NA
0.5	0.287	0.262	0.236	0.211	0.186	0.170

MTZ:Lag = 0.78

	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.354	0.375	NA	NA	NA	NA
0.2	0.335	0.316	0.334	NA	NA	NA
0.3	0.318	0.297	0.278	0.292	NA	NA
0.4	0.305	0.282	0.260	0.242	0.250	NA
0.5	0.291	0.269	0.246	0.224	0.204	0.207

MTZ:Lag = 1.73

	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.433	0.568	NA	NA	NA	NA
0.2	0.388	0.383	0.505	NA	NA	NA
0.3	0.351	0.343	0.334	0.442	NA	NA
0.4	0.325	0.311	0.295	0.287	0.368	NA
0.5	0.299	0.280	0.264	0.250	0.241	0.307

MTZ:Lag =	4.26					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.614	1.243	NA	NA	NA	NA
0.2	0.502	0.524	0.982	NA	NA	NA
0.3	0.425	0.432	0.465	0.860	NA	NA
0.4	0.368	0.368	0.368	0.387	0.737	NA
0.5	0.316	0.311	0.305	0.309	0.316	0.614

Scenario B – Mn-0.5-15 Modified GAC Treating Arsenate Contaminated Water

MTZ:Lag =	0.13					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.0850	0.0789	NA	NA	NA	NA
0.2	0.0843	0.0765	0.0702	NA	NA	NA
0.3	0.0837	0.0759	0.0680	0.0614	NA	NA
0.4	0.0831	0.0751	0.0672	0.0593	0.0526	NA
0.5	0.0822	0.0745	0.0665	0.0586	0.0508	0.0439

MTZ:Lag =	0.28					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.0884	0.0850	NA	NA	NA	NA
0.2	0.0870	0.0796	0.0756	NA	NA	NA
0.3	0.0857	0.0783	0.0707	0.0661	NA	NA
0.4	0.0844	0.0765	0.0691	0.0614	0.0567	NA
0.5	0.0831	0.0754	0.0675	0.0600	0.0526	0.0472

MTZ:Lag =	0.60					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.0969	0.1015	NA	NA	NA	NA
0.2	0.0936	0.0872	0.0902	NA	NA	NA
0.3	0.0906	0.0829	0.0762	0.0773	NA	NA
0.4	0.0877	0.0802	0.0737	0.0667	0.0663	NA
0.5	0.0837	0.0777	0.0702	0.0634	0.0562	0.0552

MTZ:Lag =	1.33					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.1151	0.1463	NA	NA	NA	NA
0.2	0.1062	0.0995	0.1300	NA	NA	NA
0.3	0.0987	0.0921	0.0884	0.1138	NA	NA
0.4	0.0921	0.0858	0.0819	0.0774	0.0975	NA
0.5	0.0863	0.0802	0.0737	0.0691	0.0638	0.0768

Scenario C – Calgon F300 GAC Treating Benzene Contaminated Water

MTZ:Lag=	0.31					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.0670	0.0650	NA	NA	NA	NA
0.2	0.0650	0.0600	0.0570	NA	NA	NA
0.3	0.0640	0.0584	0.0533	0.0501	NA	NA
0.4	0.0623	0.0568	0.0515	0.0463	0.0430	NA
0.5	0.0610	0.0550	0.0500	0.0450	0.0390	0.0360

MTZ:Lag=	0.77					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.0770	0.0800	NA	NA	NA	NA
0.2	0.0720	0.0690	0.0710	NA	NA	NA
0.3	0.0682	0.0641	0.0606	0.0624	NA	NA
0.4	0.0648	0.0603	0.0561	0.0524	0.0535	NA
0.5	0.0620	0.0570	0.0530	0.0480	0.0440	0.0450

MTZ:Lag=	2.13					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.104	0.130	NA	NA	NA	NA
0.2	0.0900	0.0920	0.115	NA	NA	NA
0.3	0.0795	0.0787	0.0801	0.100	NA	NA
0.4	0.0709	0.0689	0.0670	0.0682	0.0860	NA
0.5	0.0650	0.0610	0.0580	0.0560	0.0560	0.0720

Appendix F. Sorbent Usage Rate Data: Lead Lag Bypass Comparison

Tables displayed here present sorbent usage rate data for lead-lag arrangements with 0-50% bypass at a range of MTZ:Lag ratios. Usage rate data was compiled simulating each scenario at every potential bypass rate for a given treatment objective (C/C_o). This data was used in developing Figures 3.8 and 3.9.

Scenario A – M-3-15 Modified GAC Treating Arsenate Contaminated Water

MTZ:Lag =	**0.37**					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.283	0.260	NA	NA	NA	NA
0.2	0.282	0.257	0.234	NA	NA	NA
0.3	0.280	0.255	0.231	0.209	NA	NA
0.4	0.278	0.253	0.228	0.204	0.183	NA
0.5	0.275	0.250	0.225	0.201	0.176	0.155

MTZ:Lag =	**0.78**					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.283	0.265	NA	NA	NA	NA
0.2	0.282	0.260	0.244	NA	NA	NA
0.3	0.278	0.257	0.236	0.221	NA	NA
0.4	0.273	0.252	0.231	0.210	0.196	NA
0.5	0.268	0.247	0.225	0.204	0.183	0.171

MTZ:Lag =	**1.73**					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.287	0.286	NA	NA	NA	NA
0.2	0.280	0.269	0.274	NA	NA	NA
0.3	0.274	0.260	0.247	0.267	NA	NA
0.4	0.264	0.250	0.236	0.224	0.243	NA
0.5	0.257	0.240	0.224	0.209	0.196	0.218

MTZ:Lag =	4.26					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.319	0.398	NA	NA	NA	NA
0.2	0.299	0.305	0.409	NA	NA	NA
0.3	0.279	0.279	0.289	0.439	NA	NA
0.4	0.266	0.258	0.255	0.261	0.414	NA
0.5	0.246	0.239	0.229	0.227	0.232	0.378

Scenario B – Mn-0.5-15 Modified GAC Treating Arsenate Contaminated Water

MTZ:Lag =	0.13					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.0822	0.0745	NA	NA	NA	NA
0.2	0.0818	0.0742	0.0665	NA	NA	NA
0.3	0.0815	0.0740	0.0662	0.0586	NA	NA
0.4	0.0815	0.0737	0.0657	0.0580	0.0504	NA
0.5	0.0810	0.0734	0.0655	0.0577	0.0499	0.0423

MTZ:Lag =	0.28					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.0818	0.0748	NA	NA	NA	NA
0.2	0.0815	0.0742	0.0672	NA	NA	NA
0.3	0.0812	0.0740	0.0665	0.0597	NA	NA
0.4	0.0810	0.0734	0.0660	0.0586	0.0518	NA
0.5	0.0804	0.0729	0.0653	0.0580	0.0504	0.0437

MTZ:Lag =	0.60					
	Sorbent Usage Rate (kg/m3)					
C/C_o	0%	10%	20%	30%	40%	50%
0.1	0.0825	0.0759	NA	NA	NA	NA
0.2	0.0818	0.0753	0.0696	NA	NA	NA
0.3	0.0812	0.0742	0.0680	0.0624	NA	NA
0.4	0.0801	0.0737	0.0665	0.0600	0.0548	NA
0.5	0.0789	0.0726	0.0655	0.0591	0.0522	0.0472

MTZ:Lag =	**1.33**					
	Sorbent Usage Rate (kg/m3)					
C/C_o	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
0.1	0.0837	0.0802	NA	NA	NA	NA
0.2	0.0825	0.0777	0.0749	NA	NA	NA
0.3	0.0801	0.0754	0.0702	0.0703	NA	NA
0.4	0.0789	0.0731	0.0680	0.0634	0.0638	NA
0.5	0.0767	0.0711	0.0660	0.0604	0.0562	0.0564

Appendix G. Sorbent Usage Rate Data: Lead-Lag Without Bypass, Two-Column Parallel Without Bypass, and Single Column Without Bypass

Tables displayed here present sorbent usage rate data for single columns with and without bypass, lead-lag with and without bypass, and parallel arrangements at a range of MTZ:Lag ratios. Scenarios A and B were used to develop the data shown below. Usage rate data was used in developing summary Figures 3.10 (A & B).

Single Col. MTZ:Lag = 0.06

	Sorbent Usage Rate (kg/m3)				
C/C_o	Single Col. No BP	Single Col. W/ BP	Lead-Lag No BP	Lead-Lag W/ BP	Parallel
0.1	0.0834	0.0742	0.0831	0.0822	0.0831
0.2	0.0831	0.0680	0.0825	0.0818	0.0825
0.3	0.0828	0.0595	0.0815	0.0815	0.0815
0.4	0.0825	0.0510	0.0807	0.0815	0.0807
0.5	0.0818	0.0425	0.0713	0.0810	0.0713

Single Col. MTZ:Lag = 0.18

	Sorbent Usage Rate (kg/m3)				
C/C_o	Single Col. No BP	Single Col. W/ BP	Lead-Lag No BP	Lead-Lag W/ BP	Parallel
0.1	0.297	0.278	0.283	0.260	0.293
0.2	0.293	0.247	0.282	0.234	0.287
0.3	0.291	0.216	0.280	0.209	0.280
0.4	0.287	0.185	0.278	0.183	0.271
0.5	0.283	0.155	0.275	0.155	0.197

Single Col. MTZ:Lag =	0.28				
	Sorbent Usage Rate (kg/m3)				
C/C_o	Single Col. No BP	Single Col. W/ BP	Lead-Lag No BP	Lead-Lag W/ BP	Parallel
0.1	0.0884	0.0850	0.0825	0.0759	0.0870
0.2	0.087	0.0756	0.0818	0.0696	0.0843
0.3	0.0857	0.0661	0.0812	0.0624	0.0812
0.4	0.0844	0.0567	0.0801	0.0548	0.0773
0.5	0.0831	0.0472	0.0789	0.0472	0.0500

Single Col. MTZ:Lag =	0.60				
	Sorbent Usage Rate (kg/m3)				
C/C_o	Single Col. No BP	Single Col. W/ BP	Lead-Lag No BP	Lead-Lag W/ BP	Parallel
0.1	0.0969	0.0969	0.0837	0.0802	0.0936
0.2	0.0936	0.0873	0.0825	0.0749	0.0877
0.3	0.0906	0.0762	0.0801	0.0702	0.0812
0.4	0.0877	0.0663	0.0789	0.0634	0.0737
0.5	0.0837	0.0553	0.0767	0.0562	0.0521

Single Col. MTZ:Lag =	1.73				
	Sorbent Usage Rate (kg/m3)				
C/C_o	Single Col. No BP	Single Col. W/ BP	Lead-Lag No BP	Lead-Lag W/ BP	Parallel
0.1	0.4333	0.4333	0.3194	0.3978	0.3946
0.2	0.3877	0.3826	0.2986	0.3051	0.3298
0.3	0.3508	0.3337	0.279	0.2793	0.2797
0.4	0.325	0.2866	0.2656	0.2555	0.2376
0.5	0.2986	0.2412	0.2455	0.2275	0.2085