STATE OF NEW JERSEY
DEPARTMENT OF ENVIRONMENTAL PROTECTION
DIVISION OF SCIENCE, RESEARCH, AND TECHNOLOGY

EVALUATION AND ASSESSMENT OF ARSENIC REMOVAL TECHNOLOGIES FOR NEW JERSEY DRINKING WATER

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EXECUTIVE SUMMARY

GENERAL

To protect human health, the United States Environmental Protection Agency (EPA) recently lowered the drinking water standard for arsenic to 10 µg/L; it had previously been 50 µg/L. This new MCL (Maximum Contaminant Level) took effect on February 22, 2002, and public water systems have until January 2006 to comply.

On January 22, 2002, the New Jersey Department of Environmental Protection (NJDEP) issued a proposed regulation that would lower the New Jersey standard for arsenic to 10 µg/L and require compliance with this more stringent standard within 14 months of when the rule became effective. In addition, the rule included provisions for lowering the MCL yet further, as the revised standard does not meet the New Jersey goal of a one-in-one-million cancer risk. To this end, NJDEP commissioned the study presented herein, which was aimed at evaluating current arsenic removal technologies and establishing whether it is feasible to lower arsenic levels in New Jersey waters to below 10 µg/L. No fieldwork or laboratory analyses were included in this study. Rather, the evaluation was based on a comprehensive literature review. It should be mentioned that there have not been many pilot- or full-scale studies of arsenic removal in New Jersey. For this reason, the assessment considered national (including NJ-specific research) and international studies, as well as pilot/demonstration results, in the context of New Jersey water quality parameters and other relevant New Jersey issues.

BACKGROUND WATER QUALITY OF IMPACTED SYSTEMS IN NEW JERSEY

As part of this project, water quality information from the NJDEP Safe Drinking Water Act (SDWA) database and New Jersey Geological Society (NJGS) records was used to establish the geographical distribution of impacted systems (i.e., with arsenic levels of 3 µg/L or higher) in New Jersey. Wherever possible, water quality data specific to these utilities was considered. In cases where system-specific data was unavailable, the average water quality parameters for the appropriate physiographic region of the state were used instead.

There are 44 Community Water Systems (CWSs) in New Jersey with arsenic concentrations at or above 3 µg/L, and the majority of these produce more than 0.5 million gallons per day (mgd). There are 147 Non-transient, Non-Community Water Systems (NCWSs) with arsenic concentrations that equal or exceed 3 µg/L.

Notably, the average water quality characteristics of these systems do not preclude any established arsenic treatment technologies. In particular, background ion concentrations (e.g., phosphate, silica, sulfate) are generally below the levels that might cause interference. However, there are a few cases where the levels are such that certain technologies may be less suitable than others. For example, several of the impacted waters exhibit sulfate concentrations above 100 mg/L, the threshold level at which ion exchange treatment becomes cost prohibitive.

TREATMENT TECHNOLOGIES

Based on the findings of this study, the most feasible and cost effective treatment technologies for New Jersey waters are likely to be:

- ❑ Ion Exchange (IX)
- ❑ Activated Alumina Adsorption (AA)
- ❑ Granular Ferric Hydroxide Adsorption (GFH)
- ❑ Coagulation/Filtration (CF)

Each of these four technologies has demonstrated reliable performance for reducing arsenic levels to below method detection limits (1-2 µg/L), when processing raw waters similar to those found in New Jersey. The capital and operating costs of each technology vary depending on the influent and targeted effluent arsenic levels. In this study, preliminary cost estimates were developed using a computerized tool previously created by Malcolm Pirnie as part of an EPA-sponsored project.

With respect to ion exchange (IX), there are several impacted systems in New Jersey with sulfate concentrations above 100 mg/l, the threshold level at which IX treatment is no longer cost effective. Furthermore, IX processes generate large quantities of liquid waste and require intensive monitoring. Therefore, although IX is a reliable means for lowering arsenic levels, it may not be an attractive alternative for many New Jersey systems.

Activated alumina (AA) treatment is not likely to be affected by the background pH and silica concentrations of New Jersey waters. Overall, AA appears to be the least expensive alternative for NCWS applications (GFH is similarly cost effective). AA can be operated such that it does not generate a liquid waste stream and thus avoids potential disposal issues.

As in the case of AA, granular ferric hydroxide (GFH) treatment would not be adversely affected by the typical background quality of New Jersey waters. GFH can also be operated such that it does not generate a liquid waste stream. For this reason, GFH and AA may ultimately be the most practical alternatives for arsenic removal in New Jersey. Regarding cost, GFH appears to be the least expensive option for CWSs, although AA costs are similar.

Coagulation/Filtration (CF) and Coagulation/Microfiltration (CMF) are likely to perform well, given the typical background chemistry of New Jersey waters. However, these systems produce residuals that require some processing prior to disposal, and this will elevate their associated costs.

RESIDUALS

The general characteristics of New Jersey waters are not unique and thus the technical aspects of residuals handling will be no different than in other parts of the country. However, New Jersey does have unique surface water quality standards. In particular, the arsenic standard for surface waters is much lower than in other states; it is far below the current drinking water standard of 10

µg/L. Consequently, a wastewater treatment plant that accepts liquid residuals from an arsenic treatment system will almost certainly produce an effluent that exceeds the surface water requirement. This is true whether the drinking water standard is 10, 7, 5, or 3 µg/L. To date, this has not been a critical issue because relatively few drinking water systems have targeted arsenic removal. It is important to realize that some wastewater plants are currently receiving municipal sewage with a background arsenic level that exceeds the surface water standard.

Although this is not a true technical issue, it must still be addressed, even for the current MCL of 10 µg/l to be cost effective. If there is no change in the existing surface water standard, many wastewater plants will not be able to accept liquid residuals from arsenic treatment systems, thereby eliminating certain technologies as practical alternatives.

CONCLUSIONS

In conclusion, the general water chemistry of the impacted systems in New Jersey is such that any of the four above-listed treatment technologies could reliably reduce arsenic concentrations to 7, 5 or even 3 µg/L. The overall treatment cost will increase as the target level decreases. This information is based on a significant number of studies, although there are only a few full-scale systems operating in this country and even fewer pilot studies specific to New Jersey.

Overall, GFH and AA appear to be the most practical and economical alternatives for arsenic removal in New Jersey.

There is a significant regulatory issue associated with the disposal of arsenic-laden waste streams, and this is directly tied to the stringent surface water quality parameters that wastewater plants must currently meet. The issue exists whether the drinking water standard is 10 µg/L or some lower concentration; it will ultimately affect the feasibility and relative cost of arsenic treatment efforts in New Jersey.

1. INTRODUCTION

1.1. PURPOSE

To protect human health, the United States Environmental Protection Agency (EPA) lowered the primary drinking water standard for arsenic from 50 µg/L to 10 µg/L. All community and non-community water systems (CWSs, NCWSs) are required to comply with this revised standard by January of 2006. Due to the perceived health benefits of reduced arsenic ingestion, the State of New Jersey (NJ) is requiring compliance within 14 months of when the rule becomes effective. Furthermore, NJ is considering whether to lower the arsenic standard to below 10 µg/L. For this reason, the NJ Department of Environmental Protection Agency (DEP) initiated the work presented herein, so as to identify arsenic removal technologies that can treat the impacted waters in NJ and achieve target concentrations of 7 µg/L, 5 µg/L and 3 µg/L.

1.2. BACKGROUND

A crucial step in deciding whether to lower the NJ arsenic standard is the identification and evaluation of alternatives for arsenic removal. Chapter 2 summarizes arsenic occurrence in NJ and indicates that all of the affected supplies utilize groundwater exclusively. There are several technologies currently in use for removing arsenic from groundwater. Some of these technologies have proven to be successful in pilot and full-scale systems and are therefore referred to as "established technologies." These include:

- ❏ Ion exchange (IX)
- ❏ Adsorption by
    - ○ Activated alumina (AA)
    - ○ Granular ferric hydroxide (GFH)
- ❏ Coagulation/filtration (CF) followed by
    - ○ High-rate media filters or
    - ○ Low-pressure membrane filters
- ❏ Nanofiltration (NF) or reverse osmosis (RO)

Additionally, due to recent advances in science and the regulatory-driven need for arsenic treatment, new technologies are being developed that will ultimately improve the economics of arsenic removal from potable waters. These emerging technologies include:

- ❑ Hybrid arsenic selective adsorbents
- ❑ Nanomaterials technology based adsorbents
- ❑ Magnetic ion-exchange (MIEX™) resins
- ❑ Hydrous iron oxide particles (HIOPs)
- ❑ Sand-ballasted coagulation sedimentation (Actiflo™ process)
- ❑ Immersed membranes in combination with adsorbents and
- ❑ Microsand-assisted oxidation adsorption (Metclean™)

Chapter 3 presents a detailed discussion of these established and emerging technologies.

1.3.   SCOPE

The overall scope of this study was to identify, review, and critique treatment technologies that NJ water purveyors could implement to lower the arsenic levels of impacted waters to below 7, 5, or 3 µg/L. Arsenic removal technologies were evaluated in terms of:

- ❑ Arsenic removal efficiency (as it relates to NJ water quality)
- ❑ Technology status (pilot and full-scale observations)
- ❑ Process reliability
- ❑ Residuals handling issues

No fieldwork or laboratory analyses were conducted as part of this project. The technology assessments were based entirely on existing literature. NJ-specific conclusions were developed by evaluating these published results (which in most cases were generated outside of NJ) in terms of NJ water quality. To this end, a comprehensive list of arsenic-containing water supplies and their associated water quality characteristics was compiled using data from the NJDEP Safe Drinking Water Act (SDWA) database and from U.S. Geological Survey (USGS) reports on groundwater quality across the state (see Appendices A and B).

2.   ARSENIC OCCURRENCE IN NEW JERSEY

On January 22, 2002, the NJDEP issued a proposed regulation that would lower the NJ drinking water standard for arsenic to 10 µg/L. The proposal also indicated that the NJDEP would investigate further reductions in the arsenic standard, since 10 µg/L does not correspond to the one-in-one-million cancer risk goal identified in the NJ Safe Drinking Water Act (SDWA). Unfortunately, the arsenic concentration corresponding to such a risk is estimated to be 0.003 µg/L or 3 parts per trillion. As this is currently an unrealistic regulatory standard, the NJDEP is seeking to find the lowest achievable level.   The cancer risk corresponding to an arsenic concentration of 10 µg/L is approximately 3-4 in 1,000.

According to NJDEP SDWA databases, there are 44 CWSs in NJ with arsenic concentrations at or above 3 µg/L. These are listed in Table 2-1, which also indicates that a majority of these systems can be classified as "very large", providing more than 0.5 million gallons per day (mgd).[1] Figure 2-1 shows the locations of these CWSs, illustrating that the arsenic-laden water supplies are found throughout NJ. Figure 2-1 also identifies the five physiographic provinces of NJ, as established by the U.S. Geological Survey (USGS). Each province has a unique geology that influences the groundwater characteristics of the area, including background arsenic levels. Table 2-2 shows the relative distribution of arsenic-containing community water supplies with respect to these geological boundaries.

Table 2-3 lists the non-transient, NCWSs with arsenic concentrations in excess of 3 µg/L.[2] There are a total of 147, and they include schools, professional buildings, shopping plazas, and other public places. Although daily demand data is not readily available, the majority of these systems probably supply between 50,000 and 500,000 gallons per day (gpd) (typical range for schools, professional buildings, etc.).   Figure 2-2 shows that they are concentrated in and around the Piedmont region of New Jersey, and this is further illustrated in Table 2-2. Interestingly, there is a slightly different distribution for NCWSs than was observed for CWSs.

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[1] Water quality data for community water supplies can be found in Appendix A
[2] Water quality data for non-transient, non-community water supplies can be found in Appendix B

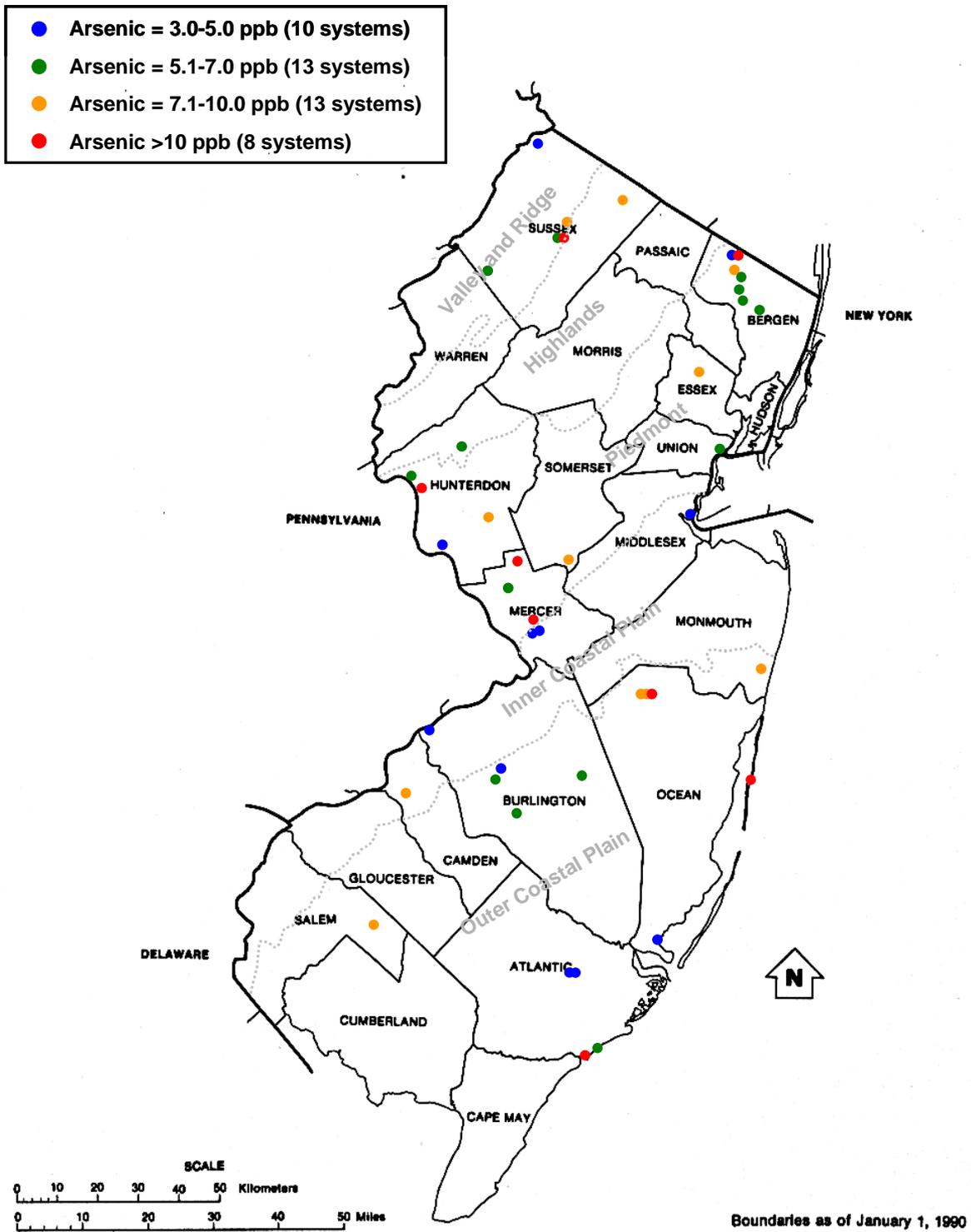**Figure 2-1. Community Water Supplies Having at Least One Source Water With Arsenic Concentrations of 3 µg/L or Higher**
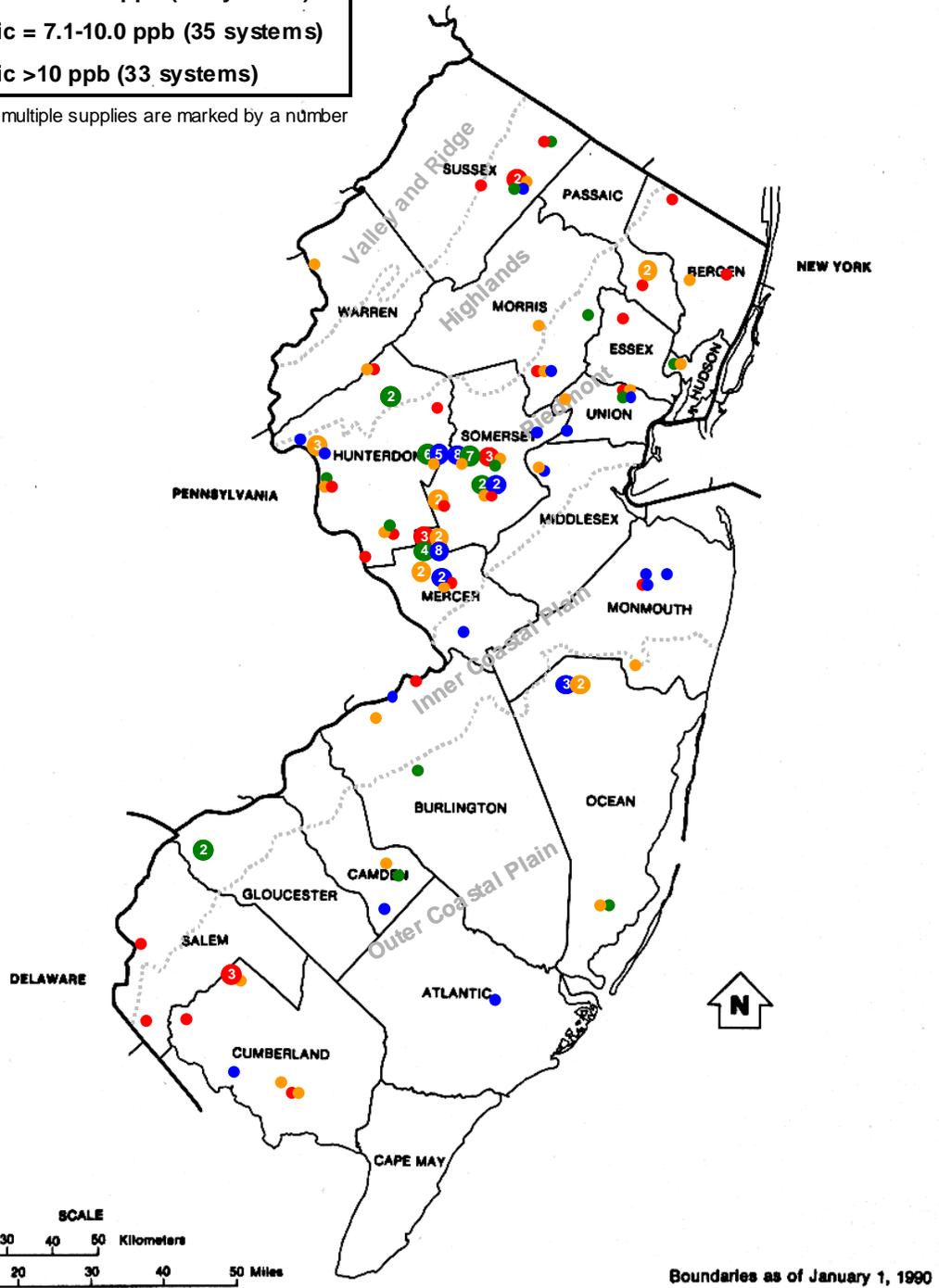
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Figure 2-2. Non-Transient, Non-Community Water Supplies Having at Least One Source Water with Arsenic Concentrations of 3 μg/L or Higher

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Table 2-1. Community Water Supplies in NJ That Have at Least One Source Water with Arsenic Concentrations Above 3 µg/L

10 Systems with Arsenic = 3.0-5.0 µg/L		
System Name	**Municipality**	**System Size**
Middlesex W. Co.	Woodbridge Twp.	Very Large
Montague Water Co.	Montague Twp.	Very Large
Mount Holly Water Company	Mount Holly Twp.	Very Large
NJ American W Co Western Div.	Palmyra Boro	Very Large
Tuckerton Water & Sewer Dept	Tuckerton Boro	Very Large
West Deptford Twp. Water Dept	West Deptford Twp.	Very Large
Bogerts Ranch Estates In	Mahwah Twp.	Large
Norms Dale Mobile Home Park	Egg Harbor Twp.	Large
Sage Investment Corporation	Egg Harbor Twp.	Large
Rosemont Water Department	Delaware Twp.	Small
13 Systems with Arsenic = 5.1-7.0 µg/L		
System Name	**Municipality**	**System Size**
Allendale Water Dept	Allendale Boro	Very Large
Clinton W Dept	Clinton Town	Very Large
Elizabethtown Water Co.	Elizabeth City	Very Large
Ho Ho Kus Water Dept	Hohokus Boro	Very Large
Longport Water Department	Longport Boro	Very Large
Monroe Twp Mua	Monroe Twp.	Very Large
Pemberton Twp Dept Main	Pemberton Twp.	Very Large
Pennington W Dept	Pennington Boro	Very Large
Ridgewood Water Dept	Ridgewood Twp.	Very Large
Waldwick Water Dept	Waldwick Boro	Very Large
Allenwood Mobile Estates	Tabernacle Twp.	Large
Milford W Dept	Milford Boro	Large
Oakview Leisure Village	Shamong Twp.	Large
13 Systems with Arsenic = 7.1-10.0 µg/L		
System Name	**Municipality**	**System Size**
Bellmawr Water Dept	Jackson Twp.	Very Large
Elmer Boro W Dept	Monroe Twp.	Very Large
Flemington Water Dept	Bellmawr Boro	Very Large
Hopewell Boro W Dept	Hopewell Boro	Very Large
Montclair Water Bureau	Flemington Boro	Very Large
Ramsey Water Dept	Hardyston Twp.	Very Large
Hardyston Twp Mua Indian Field	Hopewell Boro	Large
Rocky Hill W Dept	Frenchtown Boro	Large
Stillwater Water District	Montclair Town	Large
Vernon w Co.	Wall Twp.	Large
Vincentown Water Company	Jackson Twp.	Large
Garden State Mobile Home	Elmer Boro	N/A
Jackson Colonial Arms Ap	Lawrence Twp.	N/A

8 Systems with Arsenic > 10.0 µg/L		
System Name	Municipality	System size
Colonial Estates	Rocky Hill Boro	Very Large
Hopewell Boro W Dept	Southampton Twp.	Very Large
Lawrenceville W Co	Vernon Twp.	Very Large
Mahwah Water Department	Ramsey Boro	Very Large
Ocean Twp Mua Pebble Bea	Jackson Twp.	Very Large
Seaside Heights Water Dept	Seaside Heights Boro	Very Large
Frenchtown Water Dept	Still water Twp.	Large
Naval Air Eng. Station Lakehrs	Ocean Twp.	Large

Table 2-2. Percent Distribution of Arsenic-Containing Water Supplies Across NJ

System Type	Physiographic Province				
	Valley and Ridge	Highlands	Piedmont	Inner Coastal Plain	Outer Coastal Plain
CWS	9.3	4.7	39.5	6.3	30.2
NCWS	1.4	8.8	63.5	9.5	16.9

Table 2-3. Non-transient, Non-Community Water Supplies in NJ That Have at Least One Source Water with Arsenic Concentrations Above 3 µg/L

46 Systems with Arsenic = 3.0-5.0 µg/L		
System Name	Municipality	System Size
Curtis Specialty Papers	Milford Boro	Very Large
El Dupont Denemours & Co	Greenwich Twp.	Very Large
Lakehurst Naval Air Eng.	Jackson Twp.	Very Large
Barley Sheaf School	Raritan Twp.	Large
Alexandria Middle School	Alexandria Twp.	N/A
All Day Learning Center	Hillsborough Twp.	N/A
Allentown Caging Equipment	Upper Freehold Twp.	N/A
Applied Water Management	Hillsborough Twp.	N/A
Basking Ridge Wk Ctr/Bell Atl	Harding Twp	N/A
Bear Tavern School	Hopewell Twp.	N/A
Children's Express	Lawrence Twp.	N/A
Clinton Twp Munic Bldg	Clinton Twp.	N/A
Flemington Outlet Center	Raritan Twp.	N/A
Garvey Conveyers	Winslow Twp.	N/A
Harris Steel/Beam Ship	South Plainfield Boro	N/A
Hopewell Munic Services	Hopewell Twp.	N/A
Hunterdon County Democra	Raritan Twp.	N/A
Hunterdon Med Ctr-Well #	Raritan Twp.	N/A
Hunterdon Med Ctr-Well #	Raritan Twp.	N/A

Irwin Lincoln Mercury Ca	Freehold Twp.	N/A
Jackson Outlet Village	Jackson Twp.	N/A
Kinder Care	Burlington Twp.	N/A
Lake Nelson School	Piscataway Twp.	N/A
Laneco of Whitehouse	Readington Twp.	N/A
Liberty Court Condo Assn	Raritan Twp	N/A
Merrill Lynch	Hopewell Twp.	N/A
Migrant Day Camp	Hamilton Twp.	N/A
Minalex Corp	Readinton Twp.	N/A
Mont. Pre-Sch Cnt	Raritan Twp.	N/A
P Jax Inc.	Union Twp.	N/A
Park Meadows Industrial	East Hanover Twp.	N/A
Pennington Happy School	Hopewell Twp.	N/A
Pennington Office Park-B	Hopewell Twp.	N/A
Pennington Shop-Rite	Hopewell Twp.	N/A
Quick Check Corp	Readington Twp.	N/A
Rambling Pines Day Camp	East Amwell Twp.	N/A
Readington Farms	Readington Twp.	N/A
Route 31 Associates	Clinton Twp.	N/A
Rt 31 Professional Bldg	Hopewell Twp.	N/A
Simone Investment Group L.L.C.	Lawrence Twp.	N/A
Speedway Plaza / W. Horv	Raritan Twp.	N/A
Switlik Elementary School	Jackson Twp.	N/A
Timberlane Junior High School	Hoopewell Twp.	N/A
Victaulic Inc.	Franklin Twp.	N/A
Watchung Hill High School	Warren Twp.	N/A
Whitehouse School	Readington Twp.	N/A

34 Systems with Arsenic = 5.1-7.0 μg/L		
System Name	**Municipality**	**System Size**
Ferro Corporation	Logan Twp.	Very Large
Legends Resort & Conference	Vernon Twp.	Very Large
US Bronze Powders	Raritan Twp.	Large
Quality Partition Mfg	Kingwood Twp.	Small
B&T Development	Raritan Twp.	N/A
Camelot Nursery School	Hopewell Twp.	N/A
Center For Ed Adv (Furn.	Raritan Twp.	N/A
Children's Workshop	Hillsborough Twp.	N/A
Cross Roads Christian Academy	Franklin Twp.	N/A
Darts Mill Day Care Center	Readington Twp.	N/A
Educational Testing Services	Lawrence Twp.	N/A
First Fidelity Bank Off	Colts Neck Twp.	N/A
Flemington Circle Buick	Raritan Twp.	N/A
Giant Steps Nursery School	Harrison Twp.	N/A
Health Products Research	Readington Twp.	N/A
Hillsborough & Three Bridges	Hillsborough Twp.	N/A
Logan Generating Plant	Logan Twp.	N/A
Maur Riv Twp Bd of Ed Le	Maurice River Twp.	N/A
Ocean County Utilities	Stafford Twp.	N/A
Olde Towne Sq Condo Assoc.	Medford Twp.	N/A
Penn Partnership Parsons	Hopewell Twp.	N/A
Powerco	Union Twp.	N/A
Readington Mun	Readington Twp.	N/A
Salem Industrial Park	Readington Twp.	N/A
Salem Square	Readington Twp.	N/A
South Jersey Gas Co.	Egg Harbor Twp.	N/A

System Name	Municipality	System Size
Stage Depot	Hopewell Twp.	N/A
Stage II Motel & Prof Bldg	Hopewell Twp.	N/A
Tekni-Plex Inc.	Raritan Twp.	N/A
Three Bridges School	Readington Twp.	N/A
Transcontinental Gas Pipeline	Branchberg Twp.	N/A
Village Montessori School	Raritan Twp.	N/A
Waterford Elementary	Waterford Twp.	N/A
Yale Materials Handling	Raritan Twp.	N/A

34 Systems with Arsenic = 7.1-10.0 µg/L

System Name	Municipality	System Size
3M Mining Company	Montgomery Twp.	Very Large
Valley View Manor	Alexandria Twp.	Small
84 Components	Pennington Boro	N/A
Albert Elias Residential Group	East Amwell Twp.	N/A
B & B Poultry Co., Inc.	Pittsgrove Twp.	N/A
Bishop & Bishop (Well #2	Readington Twp.	N/A
Bristol Myers, Squibb Co Well	Hopewell Twp.	N/A
Condit Ford	Hampton Twp.	N/A
Country Mile Village	Harding Twp.	N/A
Del Rilo's Deli & Bake Shoppe	Kingwood Twp.	N/A
Delaware Valley Regional	Alexandria Twp.	N/A
GPU Energy	Howell Twp.	N/A
Harris Structural Stl Co	Piscataway Twp.	N/A
Harrisonville School	South Harrison Twp.	N/A
Inductotherm Corp	Willingboro Twp.	N/A
Jackson Memorial High School	Jackson Twp.	N/A
James Toyota	Raritan Twp.	N/A
Lester D Wilson School	Alexandria Twp.	N/A
Ming Dynasty Buffet	Stafford Twp.	N/A
Naval Air Eng Ctr/Well 4	Jackson Twp.	N/A
Oak Crest Country Day School	Franklin Twp.	N/A
Ocean County Utilities	Berkeley Twp.	N/A
Passaic County Golf Course	Wayne Twp.	N/A
Pineland Learning Center	Deerfield Twp.	N/A
Princeton Elks 2129	Montgomery Twp.	N/A
RCN Residential Comm Network	Hillsborough Twp.	N/A
Robert D Reynolds School	Upper Saddle River	N/A
Simsy's Pub	Chesilhurst Boro	N/A
Teddy & Me Daycare	Morris Twp.	N/A
The Pennington School	Pennington Boro	N/A
Townsend Property Trust L P	Hopewell Twp.	N/A
Truckstops of America	Knowlton Twp.	N/A
Union Twp School	Union Twp.	N/A
Wilson Color-Admin Well	Branchburg Twp.	N/A

33 Systems with Arsenic > 10.0 µg/L

System Name	Municipality	System Size
Seabrook Brothers and So	Upper Deerfield Twp.	Very Large
Cumberland Regional High	Upper Deerfield Twp.	Large
Little Sisters of the Poor	Totowa Boro	Medium
Seabrook House	Upper Deerfield Twp.	Small
AMI	Branchburg Twp.	N/A
ARC/Hunterdon Adult Trai	Kingwood Twp.	N/A
Arthur P Schalick High School	Pittsgrove Twp.	N/A
Breen Color	West Amwell Twp.	N/A

Discovery Years	Vernon Twp.	N/A
East Amwell Twp.	East Amwell Twp.	N/A
Esc School	Tewksbury Twp.	N/A
Fountain of Life Center	Florence Twp.	N/A
Gloucester Co Day Training	Monroe Twp.	N/A
Harding Township	Harding Twp.	N/A
Haworth Swim Club	Haworth Boro	N/A
High Road Career Center	Franklin Twp.	N/A
High Road Upper School	Franklin Twp.	N/A
Hunterdon Hills Playhouse	Union Twp.	N/A
Kooltronic, Inc.	Hopewell Twp.	N/A
Lawrence Day School	Lawrence Twp.	N/A
Lower Alloways Creek School	Lower Alloways Cr.	N/A
Mahwah BPOE	Mahwah Twp.	N/A
Pennington Office Park	Hopewell Twp.	N/A
Phillips Barber Health	Lambertville City	N/A
Salerno Duane of Sussex Inc.	Hampton Twp.	N/A
Saturn of Freehold	Freehold Twp.	N/A
The Manor	West Orange Town	N/A
Toddler Village @ Stony Brook	Hopewell Twp.	N/A
Waldorf School of Prince	Montgomery Twp.	N/A
Wilson Color – Main Well	Branchburg Twp.	N/A
Wilson Color – R & D Wel	Branchburg Twp.	N/A
Woodfern School	Hillsborough Twp.	N/A
Woodland Country Day School	Stow Creek Twp.	N/A

As previously mentioned in Section 1, the water quality characteristics for the above-listed systems were gathered from the NJDEP SDWA databases and from USGS reports regarding groundwater quality in each physiographic province. A summary of these characteristics and a discussion of their relevance to arsenic treatment in NJ are presented in Section 4.1.

3.   ARSENIC TREATMENT TECHNOLOGIES

As discussed in Chapter 1, there are several established techniques for removing arsenic from groundwater. Importantly, all of these techniques could effectively lower arsenic levels in NJ groundwater to below the detection limit (1-2 µg/L) (see Chapter 4). This chapter reviews these treatment methods, focusing on:

- ❑ Water quality characteristics that impact treatment efficiency
- ❑ Operational considerations
- ❑ Design parameters
- ❑ Residuals generation and disposal

Wherever possible, pilot- and full-scale observations were emphasized, although bench-scale results are also included. NJ-specific considerations are discussed in Chapter 4.

Note that the technologies summarized in this chapter are not the only alternatives for removing arsenic from water. Other technologies exist, but have not yet been tested in pilot- and/or full-scale systems. Also, although reverse osmosis (RO) is currently used for a wide range of full-scale applications, including arsenic treatment, it was not evaluated herein. RO uses high-pressure membrane-based technology that generates a considerable volume of liquid waste (brine). As much as 15% of the feed water becomes a brine stream that contains high concentrations of salts (making it corrosive) and arsenic (potentially causing it to be classified as hazardous). For this reason it was decided that RO would not be a practical solution for treating arsenic-containing groundwater in NJ.

3.1.   ARSENIC CHEMISTRY

Arsenic is a metal commonly found in rocks and soil, usually as part of the mineral arsenopyrite (FeSAs). Through erosion and dissolution, arsenic can enter natural ground and surface waters. Once dissolved, it can take many forms, both organic and inorganic. The organic form of arsenic usually occurs in seafood and is of relatively low toxicity. Inorganic arsenic occurs in water and is reported to be highly toxic.

The valence state and corresponding species of inorganic arsenic depend on the oxidation-reduction (redox) conditions and pH of the surrounding water. Generally speaking, the reduced, trivalent form of arsenic [Arsenite – As(III)] is found only in groundwaters, where anaerobic conditions prevail. In contrast, the oxidized, pentavalent form [Arsenate – As(V)] is observed in both groundwater and surface supplies. Either oxidation state can exist in different forms, depending on pH, and these are listed in Table 3-1.

Table 3-1. Aqueous Forms of Inorganic Arsenic

Arsenite – As(III)	$H_4AsO_3^+$, H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{2-}$, AsO_3^{3-}
Arsenate – As(V)	H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$, AsO_4^{3-}

Notably, arsenite will appear as a neutral species (H_3AsO_3) at any pH less than 9. In contrast, the neutral form of arsenate (H_3AsO_4) is only present at pH < 3. This has important implications for determining appropriate treatment technologies, as certain removal techniques rely on electrostatic attractions between arsenic and charged surfaces. These techniques, which include ion exchange, adsorption, and precipitation, are usually far more effective for removing arsenate as compared to arsenite.

Finally, although arsenic found in natural waters is typically dissolved, some research indicates that it can also appear as a particulate. An EPA report entitled *Arsenic Removal from Drinking Water by Iron Removal Plants* (EPA/600/R-00/086) explains that there have been cases where particulate arsenic accounts for 17-50% of the total arsenic concentration. This mostly occurs in surface waters, and is therefore not likely to affect arsenic treatment in New Jersey.[3]

3.2. TREATMENT LOGISTICS

As previously mentioned, the treatment technologies described below can lower arsenic concentrations to below the method detection limits of 1 or 2 µg/L. Consequently, water suppliers may prefer to treat a portion of the arsenic-laden influent stream and blend it with

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[3] Arsenic occurrence in New Jersey is limited to groundwater supplies

untreated water to achieve the target arsenic concentration. This "split-stream" approach can reduce treatment costs but may not be feasible if the arsenic standard is much below 10 µg/L.

The next several sections present technologies that are suitable for treating New Jersey groundwaters. Each technology is characterized in terms of its operational requirements, as determined in bench-, pilot-, and/or full-scale studies.

3.3. ION EXCHANGE

3.3.1. Process Description

Ion exchange (IX) is a physical/chemical process by which ions at a solid/water interface are exchanged for ions in the surrounding bulk water. The solid phase is normally a synthetic resin that preferentially adsorbs the contaminant(s) of concern. Prior to treatment, the resin is saturated with inert ions, usually chloride. During treatment, feed water is continuously passed through a packed bed comprised of this resin (usually in the form of beads) in either a downflow or upflow mode. The bed becomes exhausted when all available adsorption sites on the resin beads have been filled by contaminant ions. At this point, the bed can be regenerated by rinsing with a concentrated solution of inert ions of the type initially adsorbed to the resin. The number of bed volumes (BVs) that can be processed prior to exhaustion varies with resin type and influent water quality. It can vary between 300 and 60,000 BVs. In most cases, complete regeneration can be accomplished with only 1 to 5 BVs of regenerant followed by 2 to 20 BVs of rinse water.

Some important considerations regarding the applicability of IX for removing arsenic include water quality parameters such as pH, competing ions, alkalinity, influent arsenic concentration, and the ratio of arsenite (As III) to arsenate (As V). Other factors include the resin type, affinity of the resin for the contaminant, spent regenerant and resin disposal requirements, secondary water quality effects, and design operating parameters.
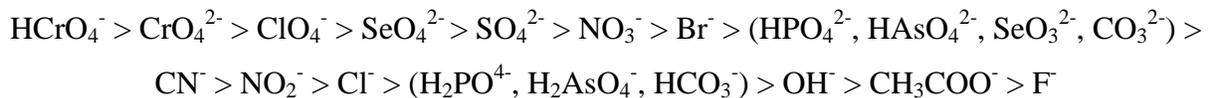
3.3.2. Water Quality Impacts

The following water quality parameters affect the performance of IX processes for arsenic removal.

- ❑ pH
- ❑ Competing ions
- ❑ Dissolved organic carbon (DOC)
- ❑ Secondary effects (caused by the treatment)
- ❑ Resin fouling

pH. The speciation of inorganic arsenic is a function of pH. If arsenic is present in groundwaters as As(III), it will normally be in a neutral form. The IX system is much more efficient at removing charged species as compared to uncharged species. Thus, IX is generally not effective for removing As(III) from natural waters. When arsenic is present in the form of As(V), the divalent $HAsO_4^{2-}$ ion is preferentially removed over the monovalent $H_2AsO_4^-$ ion. Therefore, a slightly basic pH is preferable for arsenic treatment using IX.

Competing Ions. Competition from background ions for IX sites can greatly affect the efficiency and economics of IX systems. The levels of these background ions may in fact determine the applicability of IX at a particular site. Typically, strong-base anion exchange resins are used in arsenic removal. The order of exchange for most strong-base resins is given below, with the adsorption preference being greatest for the constituents on the far left (AWWA, 2000).

$$HCrO_4^- > CrO_4^{2-} > ClO_4^- > SeO_4^{2-} > SO_4^{2-} > NO_3^- > Br^- > (HPO_4^{2-}, HAsO_4^{2-}, SeO_3^{2-}, CO_3^{2-}) >$$
$$CN^- > NO_2^- > Cl^- > (H_2PO^{4-}, H_2AsO_4^-, HCO_3^-) > OH^- > CH_3COO^- > F^-$$

Although strong base anionic resins have a relatively high affinity for arsenic in the arsenate form ($HAsO_4^{2-}$), studies have shown that high total dissolved solids (TDS) (> 500 mg/L) and sulfate levels (> 100 mg/L) can greatly reduce IX efficiency and cause short run lengths (AWWA, 2000). Recently, novel IX processes have been proposed and are currently under investigation. These processes involve the use of multiple IX columns in series with successive

regeneration of the columns, and are specifically designed for high sulfate waters (Benjamin et al., 2001).

Competitive adsorption can cause arsenic levels in the treated water to exceed the influent arsenic concentration. For example, if a resin prefers sulfate to arsenate, the sulfate ions may displace previously adsorbed arsenate ions. This is often referred to as chromatographic peaking. Because of this, the bed must be monitored and regenerated in advance of any expected peaking.

DOC. Natural waters sometimes contain significant amounts of dissolved organic carbon (DOC). The presence of DOC can affect adsorption systems by complexing with the targeted contaminants or by competing for adsorption sites. Batch tests have indicated that the adsorption capacity of IX for As(V) is dramatically reduced when the DOC concentration increases from 0 mg/L to 4 mg/L (AWWARF, 1999). However, another study found that the adsorption capacity of IX for arsenic was independent of the DOC concentrations (Vagliasindi and Benjamin, 1998).

Secondary Effects. Chloride-containing (chloride-form) resins are often used for arsenic removal. As arsenic is adsorbed onto the resin, chloride ions are released. Consequently, the chloride concentration of the product water will increase, which in turn increases its corrosivity. Chlorides increase the potential for iron corrosion and can therefore increase the potential for red water problems. In situations where chlorides pose a problem, demineralization, blending, or alternate treatment techniques may be required.

IX can reduce pH by removing bicarbonate ions, which may increase the corrosivity of the treated water. This occurs primarily at the beginning of an IX treatment cycle. The reduction in pH can be minimized by recycling the regeneration brine (that contains a high bicarbonate concentration) (Chwirka et al, 2000). In some situations, pH re-stabilization may be necessary to prevent disturbances in the distribution system. pH re-stabilization can be accomplished by adding an alkali (such as sodium hydroxide) to the IX effluent.

Resin Fouling. In the absence of adequate pre-treatment, IX resin beads may become fouled. Generally, fouling is caused by mineral precipitates (e.g., calcium or iron) or by particulates in

the feed stream (Malcolm Pirnie, 1993a). If scaling is a problem, sequestering agents can be used to lower the scale-forming potential of the feed water. If suspended solids are present, filtration upstream of the IX columns may be necessary.

3.3.3. Operational Considerations

The following operational issues affect the efficiency and overall performance of IX treatment.

- ❑ Pre-chlorination
- ❑ Resin type
- ❑ Process configuration
- ❑ Empty bed contact time
- ❑ Regeneration
- ❑ Regenerant re-use

Pre-chlorination. As previously discussed, IX resins can be effective for removing arsenate (As V) but are not effective for removing arsenite (As III). Thus, As(III) must be converted to As(V) for efficient arsenic removal. There are many oxidants that can accomplish this. One in particular that has been evaluated for arsenic removal by IX is chlorine. Tests conducted with Lake Washington water indicated that the effluent arsenic concentration from an IX column rapidly reached the influent concentration when the water had not been chlorinated (Vagliasindi and Benjamin, 2001). Even if arsenic is initially present in the As(V) form, occasionally it is possible for As(V) to revert back to As(III). Chlorination has been shown to preserve arsenic in the As(V) form (AWWARF, 1999).

While chlorine may be an effective means of preserving arsenic in the As(V) form, it should be noted that some resins are not chlorine tolerant. In some cases, the reaction of chlorine with the resin may produce nitroso-dimethylamine (NDMA), which is thought to have adverse health effects and is currently under investigation as a possible carcinogen. Potassium permanganate can also be used as an alternative pre-oxidant to convert As(III) to As(V). However, it may be possible for adsorbed As(V) to revert back to As(III) if anaerobic conditions develop in the IX media.

Resin Type. As stated earlier, strong-base resins are typically used for arsenic removal by IX. These resins, however, tend to preferentially adsorb ions such as sulfate and chloride rather than arsenate. This selective adsorption of other ions can result in chromatographic peaking if the beds are not monitored adequately. One study indicated that the removal of As(V) did not differ significantly among five different IX resins after their exchange capacity was taken into account (Clifford and Lin, 1986). When removing both nitrate and arsenic, nitrate-selective resins should be avoided because studies have indicated that the run lengths to arsenic breakthrough are higher for conventional resins than for nitrate-selective resins.

Process Configuration. While arsenic leakage sometimes occurs in IX columns, proper configuration of an IX system can prevent this as well as improve arsenic removal and help minimize regeneration frequency. In some situations, special operating methods may be needed to achieve low arsenic levels consistently. To prevent arsenic peaking, frequent regeneration is required. Another approach to avoiding sudden breakthrough is to operate several IX columns in series (Kwan et al., 2001).

Empty Bed Contact Time. Few studies have been performed to test the effect of empty bed contact time (EBCT) on IX performance. Clifford and Lin (1986) reduced EBCT from 5 minutes to 1.4 minutes in a Hanford, CA study and found no significant reduction in arsenic removal performance. In another study, four IX columns were run with EBCTs varying between 2.5 and 15 minutes (Amy et al., 1999). Data from this study indicated that the effect of EBCT on arsenic breakthrough was negligible. The advantage of shorter EBCT is reduced capital cost. However, the disadvantage of the shorter EBCT is increased regeneration frequency.

Regeneration. With chloride-form resins, concentrated NaCl solution is typically used as the regenerant. Only a few BVs of regenerant are usually required to replenish the resin, depending on the solution strength.

Regenerant Re-use. Spent regenerant will usually have high concentrations of arsenic and other sorbed contaminants. However, it may be reused many times. The arsenic level in the regenerant need not be lowered prior to reuse, although the chloride concentration must be

replenished. In a field study, an IX column was regenerated 18 times using recycled regenerant that was replenished with NaCl after each cycle to maintain the chloride concentration at 1 M (Clifford et al., 1998). Chloride addition is essential to maintain the effectiveness of the spent regenerant.

3.3.4. Design Parameters

The IX run lengths are about 1,500 BVs at a sulfate concentration of 20 mg/L and 700 BVs at a sulfate concentration of 50 mg/L (Clifford et al., 1995). If Fe(III) particulates or other suspended solids are present, they should be removed prior to the IX process for reasons previously discussed. Although a slightly basic pH is preferable for IX treatment, pH adjustment is not essential as long as the arsenic is in its oxidized (As(V)) form. If As(III) is present, it should be converted to As(V) via oxidants such as chlorine and potassium permanganate.

Typically, a 0.5 M NaCl solution is sufficient for regeneration and can be used at least 20 times before it must be treated to remove arsenic and other ions. One method for removing arsenic from the regenerant is to precipitate Fe(OH)$_3$•As or Al(OH)$_3$•As, and this is accomplished by adding iron and/or aluminum coagulants. If treating the regenerant is not a feasible alternative, the brine can be used for a single regeneration and then discharged to a public sewer. In general, the arsenic concentration in a regenerant that is used only once should be low enough so that a typical wastewater plant would accept it. Although many design parameters should be tailored to the specific treatment situation, Table 3-2 provides a useful starting point for IX design.

Table 3-2. Typical Design/Operating Parameters and Options for Ion Exchange Systems

EBCT of 2.5 minutes
Run length of 700 BVs with 20 mg/L SO$_4^{2-}$ and 1500 BVs with 50 mg/L SO$_4^{2-}$
Depth-to-diameter ratio of resin bed between 0.2:1 to 2:1
Regenerant concentration of 0.5 M NaCl
Regenerant surface loading velocity greater than 2 cm/min

3.3.5. Residuals Handling and Disposal

The primary source of residuals from an IX system is the regeneration process. With time, the efficiency of an IX resin is reduced as exchange sites are depleted. A typical regeneration requires 2.8 BVs of brine and 1.2 BVs of rinse water. Therefore, 4 to 5 BVs of residual liquid waste are produced per regeneration cycle (Amy et al., 2000).

Spent regenerant that cannot be reused must be treated and/or disposed of appropriately. This can be an expensive part of the IX process and must be given careful consideration. Spent brine can be disposed of either directly to a surface water source, or indirectly to a sanitary sewer, depending on contaminant levels. If the brine is used once, it can most likely be discharged to a publicly owned treatment works (POTW). However, if the brine is used to regenerate the IX columns several times, then some form of treatment may be necessary due to high arsenic concentrations in the brine and/or high total dissolved solids.

A recent EPA study (EPA, 2000) determined that arsenic concentrations in spent brine solutions range from 1.83 to 38.5 mg/L (average: 16.5 mg/L). Liquid residuals generated during the other steps of the regeneration process (i.e., backwash, slow rinse, and fast rinse) contained much lower arsenic concentrations (0.0594, 1.332, and 0.108 mg/L, respectively). These waste streams are often combined so as to reduce the relatively high arsenic levels in the brine wastes.

Clifford and Lin (1995) and Clifford (1999) have shown that arsenic levels in spent regenerant solutions can be reduced substantially via precipitation with iron and aluminum coagulants. In one case, a 99.5 percent arsenic removal rate was observed following the addition of ferric chloride to a regenerant solution containing 3.5 mg/L arsenic (Clifford, 1999). The ferric chloride dosage in this experiment corresponded to an Fe:As molar ratio of 20:1 (Clifford, 1999). In general, sludges generated during the treatment of spent brine solutions have passed TCLP tests, usually with less than 1.5 mg/L As(V) in the leachate. These dried sludges can therefore be disposed of in municipal landfills. The re-use of decontaminated regenerant has not yet been evaluated, but appears to be a potential option.

3.3.6. Process Schematic and Layout

A typical process schematic for an IX system is shown in Figure 3-1. The process schematic shows the operation of three vessels in parallel. IX systems are typically operated in parallel arrangement. The process schematic also shows the unit processes that are applicable for handling the spent regenerant (brine) stream. The layout for a 1 mgd, IX treatment system is shown in Figure 3-2. As shown by this figure, approximately 2,500 square feet of land area is required to install the various unit processes associated with treatment and residuals handling for a 1 mgd IX treatment system.
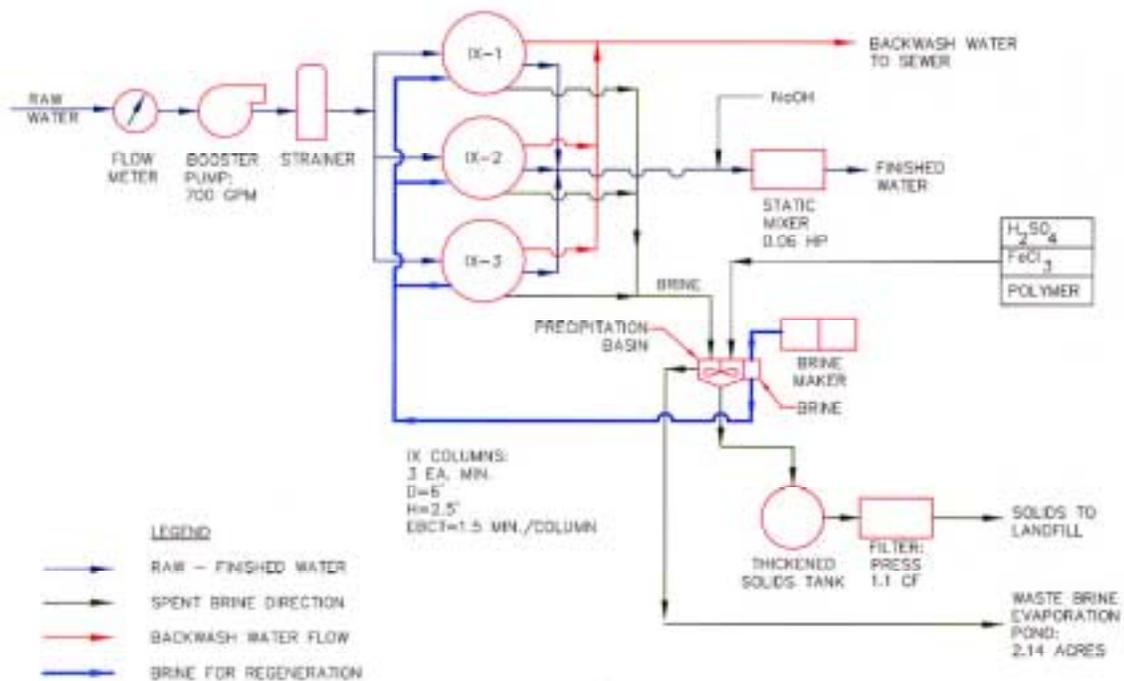
Figure 3-1. Process Flow Schematic for IX Treatment System

Labels visible in figure:
45'
55'
55 GAL. FeCl₃
IX-1 (D=6')
BRINE TANK (D=10')
H₂SO₄ TANK (D=5')
IX-2 (D=6')
NaOH TANK (D=4')
STRAINER (D=3')
BRINE MIXER (D=10')
IX-3 (D=6')
THICKENED SOLIDS TANK (D=10')
BOOSTER PUMP STATION-1 (7' X 7')
BOOSTER PUMP STATION-2 (7' X 7')
PRECIPITATION BASIN (13' X 13')
FILTER PRESS (15' X 15')
36" CURB FOR SECONDARY CONTAINMENT
WELL PUMP BASE (5' X 5')
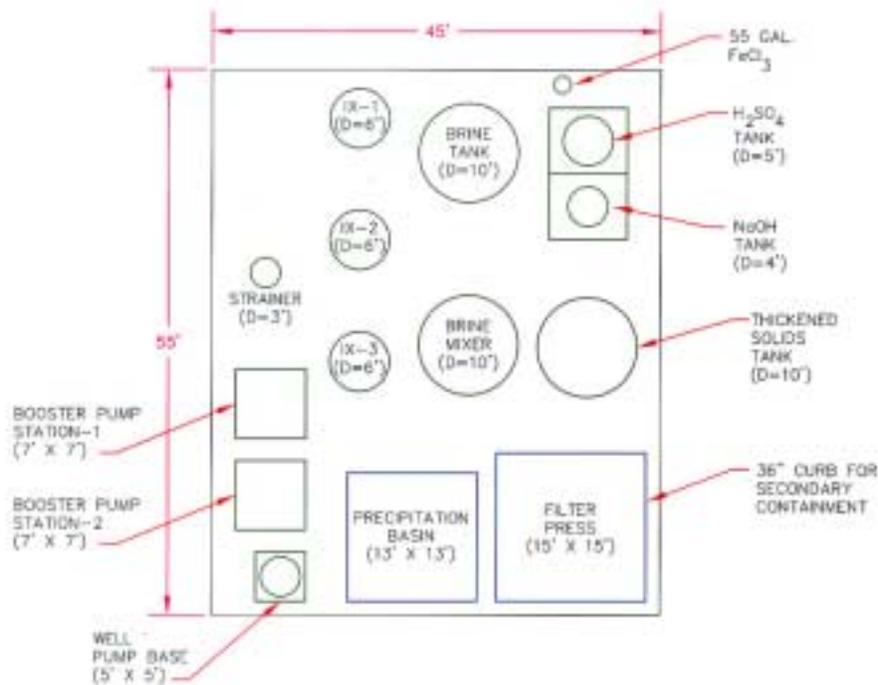
Figure 3-2. Site Layout for IX Treatment of 1 mgd Capacity

3.4. ACTIVATED ALUMINA

3.4.1. Process Description

Contaminant removal by AA is a physical/chemical process by which aqueous anions are adsorbed to an oxidized surface. AA, comprised of aluminum trioxide (Al_2O_3), is a porous, granular material with a high adsorptive capacity for negatively charged ions such as arsenic. AA media typically has a mesh size of 28 by 48 (0.3 to 0.6 millimeters in diameter) and is prepared by dehydrating $Al(OH)_3$ over a heat range of 300 to 600 ^{o}C (Clifford and Lin, 1995). It is produced by several manufacturers and is available in a variety of grades (relating to purity).

AA is used in packed beds to remove dissolved contaminants such as arsenic, fluoride, selenium, silica, and humic (organic) materials (Clifford, 1999). The target ions are captured as they are exchanged with surface hydroxides on the alumina. When adsorption sites on the AA surface become filled, contaminant removal ceases and the bed must be regenerated. Regeneration is

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accomplished through a sequence of rinsing with a regenerant solution, flushing with water, and neutralizing with acid. The regenerant is a strong base, usually sodium hydroxide; the neutralizer is a strong acid such as sulfuric acid. The AA process can also be operated on a throwaway basis wherein the spent AA media is discarded to a landfill and replaced with fresh material.

Many vendors have developed proprietary mixtures of AA with iron, manganese or other trace substances. Recent tests of these modified AA medias indicate that their adsorption capacity is similar to unmodified AA in the pH range of 7 – 8, but higher when the pH is reduced to 6.5 (NCS, 2000; Norton, et al., 2001). Treatment with AA or iron/manganese-modified AA is optimal at a pH of 5.5-6.0, at which the adsorption capacity can be as high as 500 to 1000 micrograms (µg) of arsenic per gram (g) of AA (Chowdhury et al., 2002). Adsorption capacities at higher pHs are considerably lower (Hathaway and Rubel, 1987; Clifford and Lin, 1995).

Numerous studies have shown that AA is a reliable technique for arsenic removal. Notably, factors such as pH, arsenic oxidation state, competing ions, EBCT, and regeneration have significant effect on the removal efficiency

3.4.2. Water Quality Impacts

The following are the water quality-related issues that effect the use of AA for arsenic removal.

- ❑ pH
- ❑ Arsenic oxidation state
- ❑ Competing ions
- ❑ Silica
- ❑ Fluoride
- ❑ Other ions
- ❑ Secondary effects (caused by AA treatment)

pH. Feed water pH has a significant effect on arsenic removal by AA. Unused AA is mildly basic due to the presence of excess hydroxides on its surfaces. When the media is acidified, hydrogen ions react with some of these attached hydroxies to yield water molecules, which then

surround the alumina. The anions released by the acid (chloride if the acid is HCl) are incorporated in the AA solid as counter ions. As the arsenic-laden water passes through an AA contactor, the adsorbed anions (chlorides) are displaced by arsenic (Trussel, et. al., 1980).

Importantly, AA can also adsorb cations, but only if the pH is above the isoelectric point of that material. The isoelectric point, or pH of zero-point-of-charge (pH_{zpc}), is defined as the pH at which the net surface charge of a solid substance is zero. Above this pH, the surface is negatively charged (hence allowing for cation adsorption) whereas it carries a positive charge at lower pH. For AA, the isoelectric point is between 8.2 and 9.2, depending on media purity. AA has a higher pH_{zpc} than most oxide minerals and therefore adsorbs anions in a broader pH range than the other materials.

Previous studies have indicated that the optimum pH for arsenic removal by AA is in the range of 5.5 to 6.0 (Rosenblum and Clifford, 1984). The primary benefit of acidifying the pH is that AA column runs are 5 to 20 times longer than when the pH is neutral or basic (Trussel, et. al., 1980, Simms and Azizian, 1997, NCS, 2000, Norton, et al., 2001; Chowdhury et al., 2002). Hathaway and Rubel (1987) found that AA adsorbed about 35 µg-As/g-AA when treating raw water with a pH of 9, whereas the adsorption capacity increased to 1050 µg-As/g-AA when the pH was lowered to 5.5.

Arsenic Oxidation State. In studies conducted with two column runs at pH 6, the influent for one of the columns contained 0.1 mg/L As(V) whereas the other contained 0.1 mg/L As(III). In the case where As(V) was present, the column processed about 23,400 BVs before the effluent arsenic levels reached 0.05 mg/L. The other column exhibited As(III) breakthrough almost immediately and treated only 300 BVs before the effluent arsenic concentration reached 0.05 mg/L (AWWARF Report, 2002).

Competing Ions. As in the case of IX processes, AA performance can be affected by competing ions (AWWA, 1990). The molecular structure of the AA surface is selective for fluoride, selenium, and silica species. As indicated by the general selectivity sequence shown below

(Clifford and Lin, 1995), AA preferentially adsorbs monovalent $H_2AsO_4^-$ [As(V)] over neutral H_3AsO_3 [As(III)]:

$$OH^- > H_2AsO_4^- > Si(OH)_3O^- > F^- > HSeO_3^- > TOC > SO_4^{2-} > H_3AsO_3$$

Silica. Some researchers have reported that silica can cause chromatographic peaking when the pH is above 8 (Clifford et al. 1998). This is tied to the fact that the pK_a (dissociation constant) for silicic acid is 9.5. Since silica is often present at much higher concentrations than arsenic, silica ions can compete for AA adsorption sites even though arsenic is more strongly adsorbed. Simms and Azizian (1997) confirmed this when they observed that AA media rapidly became saturated with silicate in the presence of arsenic. Furthermore, no desorption of silicate was observed after saturation. Additional studies have further reinforced that silica is a significant concern in AA systems (NCS 2000, Norton et al., 2001; Chowdhury et al., 2002).

Fluoride. Fluoride will be removed to a limited extent in AA systems. At higher levels, it may impact arsenic uptake, since fluoride will compete for adsorption sites. Recent studies conducted in Albuquerque, New Mexico and Phoenix, Arizona, established that fluoride levels in the range of 0.4 to 1.5 mg/L did not impact arsenic treatment significantly (Clifford, 1999 and NCS, 2000). Generally, the fluoride level must exceed 2 mg/L before it becomes a potential source of interference for arsenic treatment.

Other Ions. Several studies have illustrated the effects of other background ions on arsenic removal by AA. Benjamin et al. (1998) observed little effect by either sulfate or chloride at low (< 100 mg/L) concentrations. However, Clifford and Lin (1986) found that sulfate and total dissolved solids (TDS) at higher concentrations (360 mg/L and 1000 mg/L, respectively) had significant effect on adsorption, effectively decreasing the adsorption of As onto AA by approximately 50 percent.

Secondary Effects. AA processes will cause changes in treated water quality (EPA, 1994). Because these systems normally operate at low pH, caustic addition may be needed to raise the pH to a level appropriate for the distribution system.

3.4.3. Operational Considerations

The following operational issues impact the efficiency and performance of AA with respect to arsenic removal.

- ❑ Iron and manganese
- ❑ Empty bed contact time
- ❑ Regeneration
- ❑ Media fouling
- ❑ Series vs. parallel arrangement of adsorption vessels
- ❑ Other issues

Iron and Manganese.   Unlike the anionic constituents described above, cationic iron and manganese do not compete for exchange and adsorption sites on the AA treatment media. However, arsenate may attach to oxidized iron and manganese, thereby affecting removal efficiency and/or plugging the AA column (if particle sizes are large enough).   Iron and manganese concentrations of 0.5 mg/L and 0.05 mg/L, respectively, may impact AA systems, particularly if sufficient oxidation occurs prior to the treatment system. Dissolved (reduced) iron and manganese will pass through the contactor without affecting removal efficiency.

Empty Bed Contact Time. EBCT is also an important factor affecting arsenic removal. EBCT determines how long the feed water is contacted with the AA media.   Studies conducted in Albuquerque, New Mexico; Fallon, Nevada; and with Salt and Verde River Waters in Phoenix evaluated EBCTs between 1.5 to 10 minutes. These studies and the studies in Tucson, Arizona and Scottsdale, Arizona indicate that the optimum EBCT for AA is around 5 minutes (Norton, et al., 2001; Chowdhury et al., 2002).

Selection of an operating EBCT represents a compromise between improved arsenic removal rates versus the added cost of extra AA and a bigger reactor vessel. The EBCT selection should provide for sufficient run length prior to media exhaustion. It is suggested that for throwaway systems, there should be at least 3 months of operation between media replacements so as to reduce disposal costs. Typically, an AA treatment system utilizes two contactors, each with an EBCT of 5 to 7 minutes. Such a system, operating at pH 6, will typically process between

10,000 and 25,000 BVs before its media becomes exhausted (this equates to about 30 to 90 days of continuous operation).

Regeneration. Regeneration of AA beds is usually accomplished using a strong base solution such as concentrated NaOH (4% NaOH). Following this, the AA medium must be neutralized with a strong acid, typically 2 percent sulfuric acid. Clifford and Lin (1986) found that 50 to 70 percent of the arsenic in spent AA columns was removed during regeneration. Other researchers have documented the difficult regeneration of AA used for arsenic removal. Regeneration also affects successive bed life and efficiency. Bed life is shortened and adsorption efficiency is decreased by regeneration. Benjamin, et al., (1998) found that arsenic breakthrough patterns from the AA columns using regenerated media were qualitatively similar to those using fresh media, but the removal efficiency declined slightly after each regeneration. The regeneration process may reduce the bed life by 10 to 15 percent after each regeneration.

Media Fouling. AA media is susceptible to fouling. Fouling reduces the number of adsorption sites and thus decreases removal effectiveness. To prevent fouling of the AA media with particulates, the raw water may need to be filtered prior to the AA treatment. A cartridge filter or strainer with a pore size between 20 and 500 micron (µm) may be used to remove particulate matter. Two screeners or cartridge filters in parallel will ensure continuous operation during replacement or maintenance.

Series versus Parallel Arrangement of Adsorption Vessels. AA beds may be operated in series or parallel. Series operation increases removal and helps prevent leakage, but limits throughput (leakage simply refers to elevated levels of arsenic in the treated waters). Parallel operation on the other hand increases throughput, but does not improve treated water quality (AWWA, 1990). When operated in series, a "merry-go-round" configuration is often used. This configuration uses three beds: two in production and one in regeneration mode at a given time. When exchange capacity of the first bed in series is exhausted, the first bed is removed from service to be regenerated. The second bed in series then becomes the first and a fresh regenerated bed is brought on-line to become the second.

Other Issues. Degradation of AA media must also be considered. Alumina tends to dissolve over successive regeneration cycles due to the strong base/strong acid that are used. Strong acid and strong base are handled on a frequent basis for pH adjustment and regeneration purposes and can present a safety hazard. An operator must be capable of handling these chemicals.

3.4.4. Design Parameters

The removal of arsenic by AA depends primarily on pH. The AA utilization and arsenic removal rates decrease rapidly as pH increases from 6.0 to 9.0. The optimal pH range for arsenic removal using AA is typically reported to be 6.0 or less (Chwirka, 2000; Rosenblum and Clifford, 1984). Therefore, a process decision must be made as to which of the following is preferable: a) acidifying the influent water or b) replacing the media on a frequent basis. Adjusting pH can be challenging when confronted with high ambient pH and/or high levels of alkalinity. Table 3-3 provides typical design parameters for AA systems targeting arsenic.

Table 3-3. AA Design Parameters

Feedwater pH	EBCT (min)	Anticipated Bed Life (Bvs)
< 6.0	3-5	6,000-20,000
6.0-8.0	5-7	1,000-10,000
>8.0	7-10	<1,500

Other design recommendations include (Clifford, 1999; Chwirka, 2000; Chowdhury et al., 2002):

    Media bed depth – 3 to 5 feet

    Bed approach velocity – 4 to 8 gal/min-ft^2

    Particle size – 28 by 48 mesh size

If the AA media is regenerated then the design considerations for regeneration will include:

    Regenerant concentration – 0.25 N to 1.0 N NaOH

Regenerant volume – 4 to 5 bed volumes

Acid rinse – 0.4 N H_2SO_4

Acid rinse volume – 1.5 to 4 bed volumes

3.4.5. Residuals Handling and Disposal

AA with On-Site Regeneration. Once the AA has reached its adsorptive capacity (exhaustion), the media can be regenerated for a subsequent column run. Regeneration of AA is accomplished by a series of steps: (1) backwashing with raw water; (2) regenerating with a base, typically caustic soda; (3) neutralizing with acid, typically sulfuric acid; and (4) rinsing with raw water. Conventional AA requires regeneration once every one to three months, depending on the operating frequency of the well and the influent water quality (NCS, 2000; Norton, et al., 2001).

To regenerate AA, a dilute caustic soda solution (0.25-1.0 N) is passed through the bed in a downflow mode. It takes approximately 2,000 pounds of pure caustic soda to regenerate a 1 million gallon per day (MGD) facility (NCS, 2000). Following regeneration, dilute sulfuric acid (pH 4.0) is required to re-acidify the bed. A small portion (approximately 2 percent) of the AA media is dissolved during regeneration due to the elevated pH conditions (Chwirka, et al., 2000).

The liquid waste stream produced by regeneration and media re-acidification is likely to be classified as a hazardous waste, since it will probably have arsenic concentrations exceeding 5 mg/L. Typical residuals handling requirements for AA system include an arsenic precipitation basin for regenerant waste and acid rinse waste, sulfuric acid facilities to precipitate arsenic from the spent regenerant (arsenic will adsorb to aluminum hydroxide precipitate at a pH of approximately 6.0), and solar drying beds to dewater underflow solids from the precipitation basin. Recovered water from the precipitation basin may be discharged to a sanitary sewer (where allowed) or it may have to be evaporated in brine lagoons (where direct sewer disposal is not allowed due to high TDS levels).

Disposable AA. AA can also be used as a disposable media. Under this option, the media would be replaced upon exhaustion. This option is especially attractive when run lengths of several months to more than one year are possible. A small concrete staging area would be

required to stockpile media used prior to landfill disposal. The exhausted media is expected to pass the TCLP test and be classified as a non-hazardous waste (Amy et al., 2000; Chowdhury et al., 2002). Systems that operate on a throwaway basis will not face the disposal issues associated with concentrated brine wastes.

3.4.6. Process Schematic and Layout

Figures 3-3 and 3-4 show the process schematics for AA treatment with one and multiple trains, respectively.
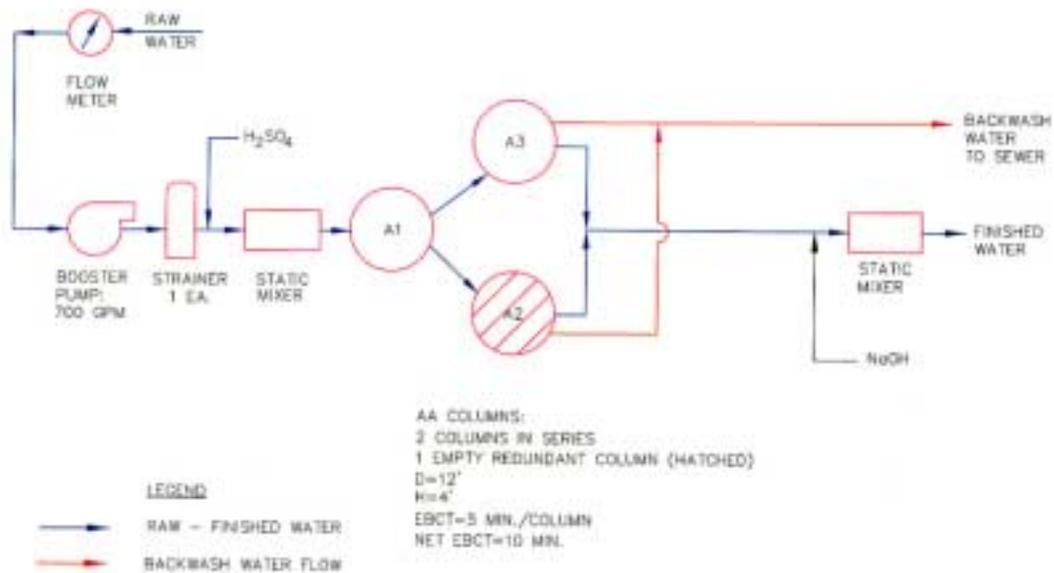
Figure 3-3. Process Flow Schematic for AA Treatment with Single Train
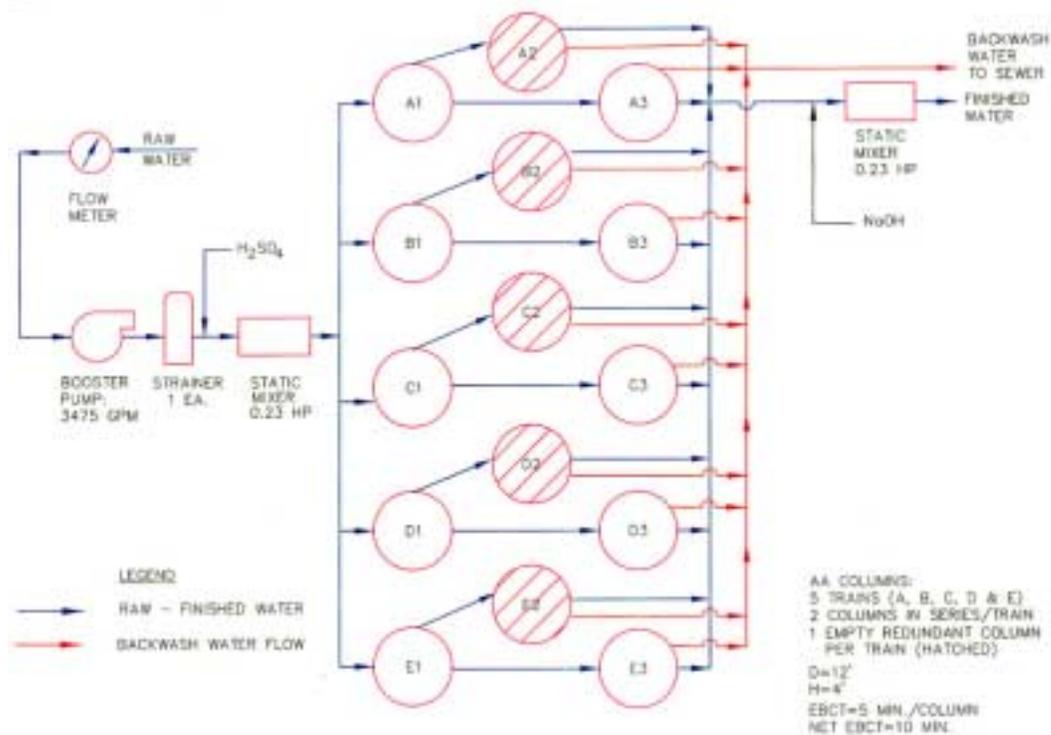
Figure 3-4. Process Flow Schematic for AA Treatment with Multiple Trains

Typically, one AA treatment train is used for treating flows up to 1 mgd capacity. For large systems (e.g., 5 mgd), multiple trains as shown in Figure 3-4 are used. The process schematics shown in Figures 3-3 and 3-4 illustrate the AA treatment in series mode with a redundant vessel. In this mode, the roughing vessel and polishing vessel are operated in series and when the media in the roughing vessel is exhausted, the flow is switched to make the polishing vessel the roughing vessel and the redundant vessel the polishing vessel. As shown in the process schematics, a typical AA treatment system will have a strainer to remove particulates and well debris, followed by an acid addition step (if the raw water pH is basic).

Figures 3-5 and 3-6 illustrate the layouts for 1 mgd and 5 mgd AA treatment systems. A 1 mgd AA treatment system would need about 2,000 square feet of area while a 5 mgd AA plant would need about 6,000 square feet of area.
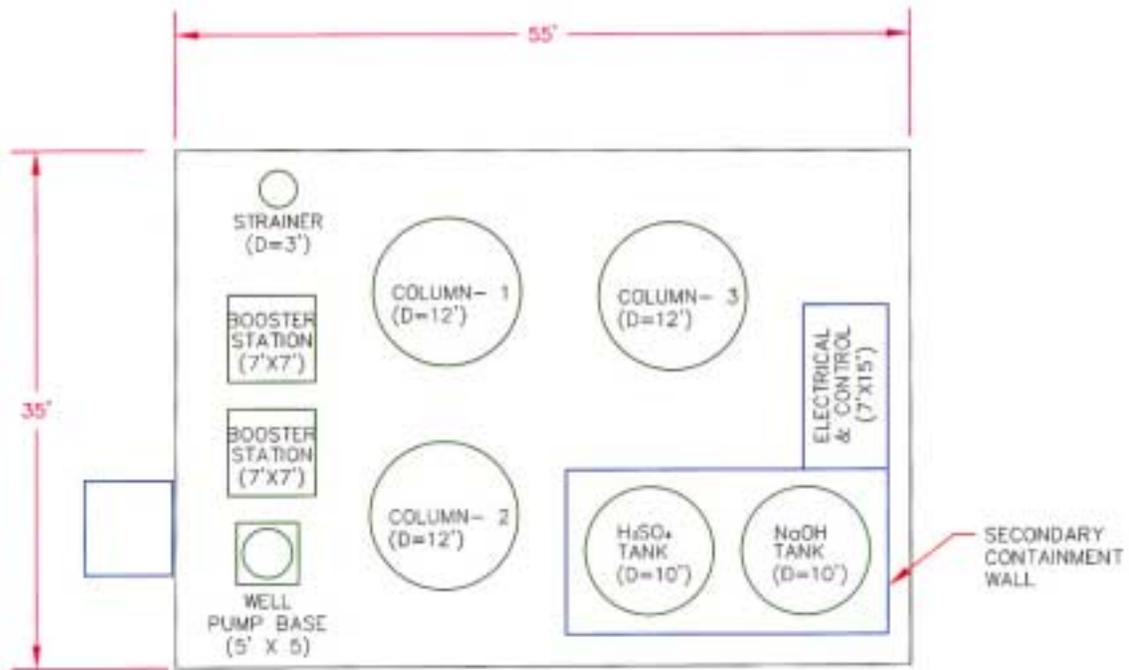
Figure 3-5. Site Layout for 1 mgd AA Treatment Plant
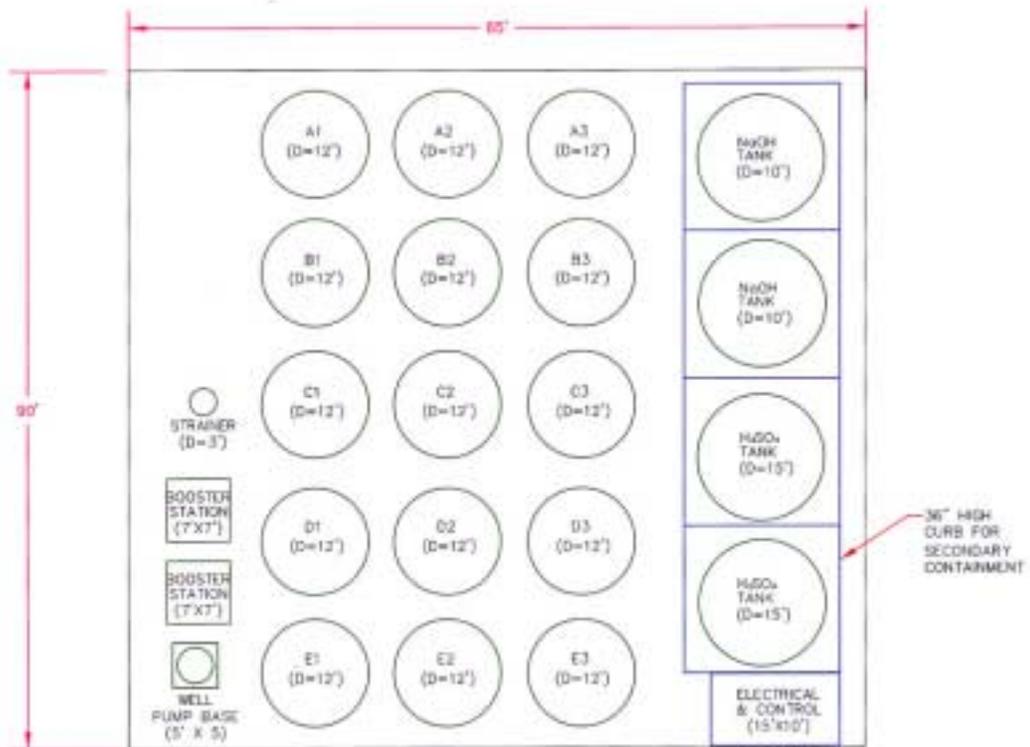
Figure 3-6. Site Layout for 5 mgd AA Treatment System

3.5. GRANULAR FERRIC HYDROXIDE

3.5.1. Process Description

GFH is an iron based media adsorbent developed at the Technical University of Berlin in 1994 (Driehaus, 2000). GFH is employed in fixed-bed pressure vessels, similar to IX and/or AA systems, and is currently being used for arsenic treatment at several locations throughout Europe (GEH Wasserchemie, 2001). It should be noted that there are other iron-based media that have also been employed for arsenic removal. These include:

❑ An iron-based media developed by Bayer AG (Europe) and Severn Trent (UK). This media is being used for arsenic treatment at locations in the United Kingdom (Selvin et al., 2001);

❑ G2 media developed by ADI group (Canada) and reportedly being employed at locations across North America and Japan.

Except for the Bayer product, the other media could be considered a modified adsorbant that relies on iron for enhanced performance. Conversely, GFH and the Bayer media are primarily comprised of granular iron oxide. The remainder of this section primarily addresses the use of GFH (GEH Wasserchemie, 2001), however, the commentary may also apply to other iron-based media (Selvin, et al., 2001).

GFH is a weakly crystalline-ferric oxyhydroxide (FeOOH), produced by conditioning a previously-compacted, iron hydroxide slurry (Jekel and Seith, 2000). The chemical composition of GFH is 52 to 57 percent FeOOH and 43 to 48 percent water (Jekel and Seith, 2000). Its physical properties are summarized in Table 2-3. Under certain water quality conditions, GFH has been shown to process more than 100,000 BVs of water prior to regeneration/replacement (Driehaus et al., 1998 and Simms et al., 2000). Its adsorption capacity for arsenic is reported to be as high as 45 mg-As/g-GFH (GEH, 2001). Presently, there are a number of full-scale plants in Germany and England that use GFH adsorption processes for arsenic removal (Driehaus et al., 1998, Simms et al., 2000 and Selvin et al., 2000). The GFH media is NSF 61 certified for use in potable water applications (Norton, et al., 2001, Chowdhury et al., 2002).

Table 3-4. Physical Properties of GFH Media

Physical Properties	Reported Values*
Iron density, kg/L	0.38
Grain density, kg/L	1.59
Packing density, kg/L	1.22-1.29
Grain size, mm	0.32-2.0 (5% < 0.32 mm; 5-10%, >2 mm)
Particle porosity, %	72-77
Bed porosity, %	22-28
Specific surface, m^2/g	250-300

Source: Driehaus et al., 1998; Jekel and Seith, 2000.

3.5.2. Water Quality Impacts

The following water quality-related issues affect the use of GFH for arsenic removal.

- ❑ pH
- ❑ Arsenic oxidation state
- ❑ Competing ions

pH. The arsenic adsorption capacity of GFH is affected by pH (Jekel and Seith, 2000, Norton, et al., 2001, Chowdhury et al., 2002). Driehaus et al. (1998) report that in batch tests, a two-fold reduction of arsenic uptake occurred when the pH was raised from 6 to 8. The following field studies (pilot-scale and larger) also document pH effects:

Scottsdale, Arizona. For a pilot system treating 2 gpm well water (EBCT = 12.5 minutes) at a pH of 9 (source water pH), arsenic breakthrough was observed after 2,700 bed volumes. Fifty percent breakthrough occurred after 3,500 BVs. The pH was then decreased to between 7 and 8 and the treated water arsenic level decreased significantly (Norton, et al., 2001, Chowdhury et al., 2002).

Tucson, Arizona. For a pilot system treating 5 gpm well water (EBCT = 5 minutes) at a pH of 7.2-7.5, there was no arsenic breakthrough (0 percent of an average influent arsenic concentration of 15 µg/L) until 26,000 BVs had been processed (Norton et al., 2001, Chowdhury et al., 2002). Treated water arsenic concentrations remained below 10 µg/L until 96,000 BVs.

Germany. For a full-scale system treating well water at a rate of 233.4 gpm (EBCT = 5.7 minutes), 30 percent breakthrough occurred at 60,000 BVs (pH = 7.9). Treated water arsenic concentrations dropped to 10 percent of the influent concentration when the pH was lowered to 7.0 (Jekel and Seith, 2000).

Arsenic Oxidation State. GFH media does not appear to be highly selective for As(V) as compared to As(III) (GEH Wasserchemie 2000; Selvin et al., 2000). Simms (2000) suggested that the granular iron media has an oxidizing effect on As(III), so pre-oxidation may not be necessary.

Competing Ions. Anions including silica, phosphate, sulfate, and fluoride are also adsorbed by GFH (Driehaus et al., 1998 Norton et al., 2001, Chowdhury et al., 2002). As with other adsorptive technologies, competitive adsorption can reduce arsenic uptake. Among the competing ions, phosphate appears to have the greatest impact on the arsenic removal performance of GFH (Jekel 2001).

3.5.3. Operational Considerations

The following operational issues impact the efficiency and performance of GFH treatment for arsenic removal.

- ❑ Empty bed contact time
- ❑ Regeneration
- ❑ Media fouling
- ❑ Other issues

Empty Bed Contact Time. The EBCTs reported for GFH systems are typically shorter than those for AA systems. A pilot system in England effectively removed arsenic while operating

with an EBCT of merely 3 minutes (Selvin et al., 2000), and there is a full-scale prototype, also in England, that is currently operating with the same EBCT (Simms, 2000). A review of 17 full-scale and pilot-scale systems (0.7 gpm to 700 gpm) in Germany indicate that the average design EBCT for these systems is 4.7 minutes. However, because they often process water at rates that are far below their design flow, the average actual EBCT is 12.5 minutes. Pilot studies in Arizona showed effective arsenic removal by GFH at EBCTs between 5-12.5 minutes (Norton et al., 2001, Chowdhury et al., 2002).

Regeneration. Facilities using GFH are not currently regenerating their media (Jekel 2001). Regeneration has been suggested but is not recommended (Driehaus et al., 1998). Upon exhaustion, the media is being disposed of according to local regulations. The spent media exhibits a low water content and therefore does not require significant dewatering (other than gravity drainage) prior to disposal. The strong affinity of arsenic to the GFH media suggests that the mildly acidic TCLP analysis will not cause significant arsenic elution. In one TCLP study, the spent GFH media produced a leachate containing less then 5 µg/g of arsenic (Selvin et al., 2000).

Media Fouling. GFH systems can become fouled if there is a significant concentration of suspended solids in the feed water. Over time, these particulates coat the GFH granules and thereby prevent arsenic removal. This can be avoided by installing a pre-filter upstream of the contactor. Backwashing at regular intervals may also be an option (Selvin et al., 2000).

Other Issues. Some of the considerations for GFH treatment include: a) the need to keep GFH media continuously wet (prior to and during use) and b) the relatively fragile nature of the material.

3.5.4. Design Parameters

The use of iron-based media such as GFH to remove arsenic from water supplies appears to be a promising alternative. The technology is gaining acceptance in Europe and is being used in place of other technologies such as AA. This is due in part to longer treatment runs, less sensitivity to pH (although the process is more effective at lower pH values), reported removal of

both As(III) and As(V) species, and more manageable residuals (that do not require extensive dewatering).

There are approximately 17 plants in Germany that currently use the GFH media (US Filter-GEH, 2001). Some of these plants have reported operational lifetimes of more than 3 years (240,000 BVs) when they operate intermittently at a low pH. On average, these plants operate for about 12 to 14 hours per day. This intermittent operation apparently improves the GFH performance by allowing for more complete diffusion of arsenic into the pore structure (Jekel, 2001).

The design parameters of Table 3-5 were developed based on the operational data of existing plants in Europe and pilot systems in the U.S.

Table 3-5. GFH Design Parameters

Feedwater pH	EBCT (min)	Anticipated Bed Life (BVs)
6.5-7	3-10	110,000
7-7.5	3-10	75,000

Other design recommendations include (GEH Wasserchemie, 2001; Jekel, 2001; Selvin et al., 2000):

Media bed depth – 2 to 5 feet
Bed approach velocity – 5 to 8 gal/min-ft^2
Particle size – 0.32 to 2 mm
Tolerable headloss – 1 psi/ft

3.5.5 Residuals Handling and Disposal

Disposal options for GFH media are assumed to be similar to those for AA media, namely landfill disposal as a non-hazardous solid waste. After exhaustion, the media would likely go through some sort of preliminary draining to minimize free liquids. This drainage is assumed to

occur within the treatment vessel or during post treatment. The GFH media would be subject to local disposal regulations in addition to national standards, including the TCLP test. The strong adsorption of the arsenic on the GFH media suggests that the media would not release arsenic. In TCLP tests of spent GFH media, the resultant leachate contained less then 5 µg/g of arsenic (Selvin, et al., 2000, Norton et al., 2001).

3.5.6   Process Schematic and Layout

The process schematics and footprints for GFH adsorption systems will be similar to those shown for AA adsorption.

3.6.   COAGULATION/FILTRATION

3.6.1. Process Description

Coagulation/filtration systems are available as package systems and therefore can be used for wellhead treatment. The filtration can be accomplished using either high-rate media filters or low-pressure membrane filters. This section focuses on coagulation followed by high-rate media filtration and the next section discusses coagulation-assisted membrane filtration.

Removal of arsenic by coagulation/filtration (CF) can be achieved via two mechanisms: adsorption and occlusion/co-precipitation. Adsorption during coagulation occurs when dissolved contaminants attach themselves to particles resulting from the precipitation of metal hydroxides (formed from coagulants such as aluminum sulfate, ferric chloride, and ferric sulfate). Occlusion/co-precipitation occurs when a dissolved species adsorbs to the surface of a growing particle and is then entrapped by continued agglomeration (Benefield and Morgan, 1999). In other words, the conditions that control nucleation and growth of metal hydroxide precipitates might affect the efficiency and degree of arsenic removal during coagulation.

3.6.2. Water Quality Impacts

The following water quality-related issues affect arsenic removal by coagulation/filtration.

- ❑ Arsenic oxidation state
- ❑ Initial arsenic concentration
- ❑ Co-occurring solutes

Arsenic Oxidation State. Coagulation with metal salts is more effective at removing As(V) than As(III). Therefore, in cases where As(III) is present, it is useful to precede coagulation with and oxidation step that converts As(III) to As(V).

Initial Arsenic Concentration. Studies have shown that in precipitative processes, arsenic removal efficiency is often independent of the initial arsenic concentration, particularly at the levels normally found in drinking water supplies (Cheng et al., 1994; Hering, 1997).

Co-occurring Solutes. Background ions and dissolved organic matter can affect arsenic adsorption and therefore may impact arsenic removal during coagulation. Hering et al. (1996) and Hering and Elimelech (1996) investigated the effects of sulfate and natural organic matter on As(III) and As(V) removal during coagulation with ferric chloride (4.9 mg/L). The results indicated that As(III) removal is more sensitive to changes in background levels of sulfate and/or natural organic matter. In general, As(V) removal efficiencies were unaffected by changes in background water quality at any pH below 8. Conversely, As(III) removal declined with increasing levels of sulfate and/or organic matter in a wide range of pH values.

3.6.3. Operational Considerations

The following operational issues impact the efficiency and performance of coagulation/filtration treatment of arsenic.

- ❑ Coagulant type
- ❑ Coagulant dosage
- ❑ Coagulation pH

Coagulant Type. On a molar basis, alum and iron salts provide about the same level of arsenic removal (Edwards, 1994). However, on a weight basis iron salts are superior (Sorg and

Logdsdon, 1978; Chen et al., 1994; Scott et al., 1995). Also, iron salts are effective in a wider pH range than alum.

Based on experimental data found in the literature and on the results of batch coagulation experiments, Edwards (1994) determined that on a molar basis (moles of iron vs. moles of aluminum), iron and aluminum coagulants are equally effective for removing As(V) at pH values below 7.5. However, the use of an iron-based coagulant is advantageous above pH 7.5 because of its lower solubility under basic conditions.

Effect of Coagulant Dosage. Studies have indicated that coagulant dose can affect arsenic removal (Kommineni et al., 2002; Cheng et al., 1994; Edwards, 1994; Gulledge and O'Conner, 1973). In general, as coagulant dosages are increased, removal efficiencies also increase. Hering et al. (1996) observed that coagulant dose had a pronounced effect on the removal of both As(III) and As(V). Under comparable conditions, As(V) was more efficiently removed than As(III). Notably, at ferric chloride dosages above 5 mg/L, residual As(V) levels were below detection limits (the initial arsenic concentration was 9 and 20 μg/L).

Coagulation pH. Several studies have reported that pH can influence the arsenic removal rates achieved by coagulation processes. Sorg and Logsdon (1978) noted that As(V) removal with alum coagulation is most effective in the pH range of 5 to 7, and that ferric coagulation is most effective in the slightly broader pH range of 5 to 8. Sorg and Logsdon (1978) indicated that As(V) removal by coagulation with iron salts is not pH-dependent in the pH range of 5.5 to 8.5. They also stated that As(V) removal using alum begins to decline significantly above pH 7.

3.6.4. Design Parameters

Robinson (2001) reported on the experience of a 9 mgd facility in Kokomo (Indiana) that treats arsenic-contaminated groundwater (arsenic concentration > 0.9 mg/L). At this facility, raw water is aerated to remove hydrogen sulfide and to partially oxidize arsenic, manganese, and iron. This is followed by chemical oxidation with potassium permanganate and chlorine. Ferric sulfate or ferric chloride (2-4 mg/L) is then added, in addition to an anionic polymer (0.25 mg/L). Filtration is accomplished by means of high rate, dual media gravity filters. Overall, the

arsenic concentration in the finished water is 98 percent lower than the influent level. Due to high levels of arsenic in the sludge produced at this facility, special residuals handling is required. The sludge is conditioned with an inorganic polymer, pressed to approximately 30 percent dry solids, tested for toxicity, and disposed as special waste in a sanitary landfill.

3.6.5. Residuals Handling and Disposal

As discussed above, the primary residual waste generated by coagulation/filtration methods is an arsenic-laden sludge mostly comprised of metal hydroxides. Depending on TCLP tests, this material may or may not be categorized as a hazardous waste. Based on previous findings, it is likely that in most cases, these residuals will be suitable for sanitary landfills. Depending on the quantity of solids generated during treatment, yet another disposal option may be to discharge the suspended floc (i.e., from a filter backwash cycle) to a sanitary sewer.

3.6.6. Process Schematic and Layout

The process schematic for coagulation-assisted, high-rate media filtration will be similar to the coagulation-assisted microfiltration. The footprint for coagulation/filtration will be slightly larger than the footprint of the coagulation/microfiltration system. Refer to the next section for the process schematic and footprint of a coagulation/microfiltration system.

3.7. COAGULATION/MICROFILTRATION

3.7.1. Process Description

The ability of microfiltration (MF) to remove arsenic is highly dependent on the size distribution of arsenic-bearing particles in the source water. Typical MF pore sizes are too large to substantially remove dissolved or colloidal arsenic. Therefore, MF alone is not a viable technique for arsenic removal for groundwaters. Coagulation microfiltration (CMF) processes are modified coagulation/filtration processes in which MF or ultrafiltration (UF) are used in place of a conventional granular media filter. Depending upon the source water quality, MF or UF may be used in either a direct filtration (coagulation, flocculation, membrane filtration) or more conventional (coagulation, flocculation, sedimentation, membrane filtration) application. CMF is capable of removing smaller particle floc which results in decreased coagulant dosage

45

and increased plant capacity. Source waters with high As(III) concentrations may require pre-oxidation with chlorine, permanganate or ozone to convert As(III) to As(V).

Vickers et al. (1997) and Kommineni et al. (2001) reported that CMF exhibited excellent arsenic removal capabilities. This report is corroborated by pilot studies conducted by Clifford (1999), which found that CMF could reduce arsenic levels to less than 2 μg/L in waters with a pH between 6 and 7, even when the influent concentration of Fe(III) is approximately 2.5 mg/L. These studies also found that the same level of arsenic removal could be achieved when source water sulfate and silica levels were high. Kommineni et al. (2001) conducted pilot-scale evaluations with CMF for the removal of arsenic from both groundwater and surface water sources. Preliminary test results are summarized in Table 3-6.

Table 3-6. **Summary of Coagulation Assisted Membrane Processes Removal Capabilities**

Membrane Type	Nominal Pore Size (μm)	Source Water Type	Source Water Turbidity (NTU)	Coagulant ($FeCl_3$) Dose (mg/L)	Influent As Concentration (μg/L)	Final As Concentration (μg/L)
UF	0.035	Surface	20 - 3000	5 - 200	1.3 - 6.7	<1*
UF	0.01	Surface	20 - 3000	5 - 200	1.3 - 6.7	<1
MF	0.1	Surface	20 - 3000	5 - 200	1.3 - 6.7	<1
MF	0.2	Surface	20 - 3000	5 – 200	1.3 - 6.7	<1
MF	0.2	Ground	NA	0.6 - 1.4	10 - 20	< 2 - 6**

NA: Not Available; * Method detection limit was 1 μg/L; ** Method detection limit in this case was 2 (μg/L)

Coagulant doses for the surface water tests presented in Table 3-6 varied significantly due to seasonal fluctuation in source water turbidity. However, in all cases finished water turbidities remained below 0.1 NTU. The ground water source used in these experiments was of high quality and coagulant was added solely for the purpose of arsenic removal.

Chwirka et al. (2000) evaluated CMF for removal of arsenic from a groundwater with an average source water arsenic concentration of 52 µg/L. The average source water alkalinity was 164 mg/L (as CaCO$_3$), sulfate was 55 mg/L, silica was 29 mg/L, and pH was 8.5. When sufficient ferric chloride (5 - 22 mg/L) was added to reduce the pH to 7.3, coagulation assisted microfiltration consistently reduced the arsenic concentration to less than 2 µg/L. The pH adjustment was necessary to minimize the silica interference with the coagulation process, which is nearly eliminated at pH less than 7.

3.7.2. Residuals Handling and Disposal

Residuals generated by CMF processes consist of a backwash stream containing dilute ferric or aluminum hydroxide precipitate depending on the type of coagulant utilized. The solids content of the backwash from CMF processes was found to be less than 0.5 percent in one study (Clifford et al., 1997).

Disposal options for arsenic-laden CMF residuals are largely dependent on the total concentration of arsenic and of suspended solids in the residual stream. If the residuals exceed the allowable NPDES limits, then disposal by direct discharge to surface water is not acceptable. Indirect discharge may be an option depending on local POTW limits. If these two alternatives are not available then further treatment to remove arsenic from the liquid residuals or to concentrate the residuals into solid form for land disposal may be necessary.

3.7.3. Process Schematic and Layout

Figure 3-7 shows the process flow schematic for CMF. This figure shows two parallel MF trains that are fed with coagulated water. The process schematic also illustrates the various unit processes associated with handling the backwash water.

Figure 3-8 shows the layout for a 1 mgd CMF treatment plant. Approximately, 4,000 square feet of area is required to install the various unit processes associated with a 1 mgd CMF treatment system.
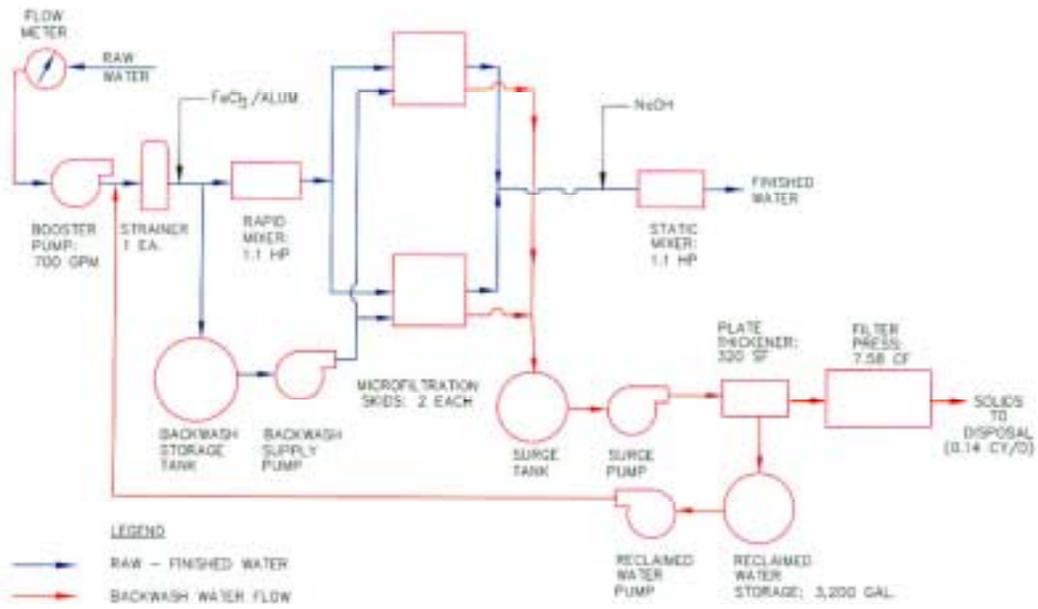
Figure 3-7. Process Flow Schematic for CMF Treatment System
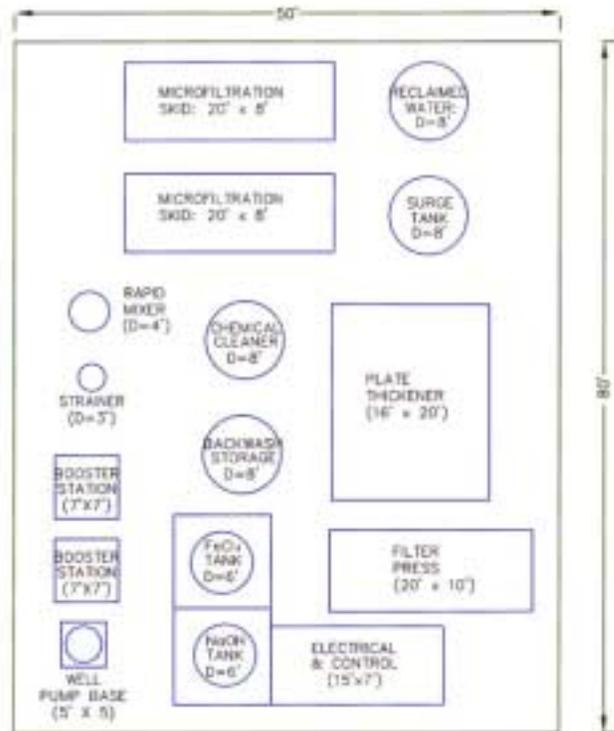
Figure 3-8. Site Layout for 1 mgd CMF Treatment System

3.8.   OTHER TREATMENT TECHNOLOGIES

There are a number of processes that are emerging as promising technologies for arsenic removal.   However, at present there is very little information regarding the full-scale applicability of these methods, and so they could not be evaluated in the context of this report. These include:

- ❑ Magnetic ion-exchange (MIEX®) resin
- ❑ Hydrous iron oxide particles (HIOPs)
- ❑ Sand-ballasted coagulation sedimentation (Actiflo™ process)
- ❑ Immersed membranes in combination with adsorbents
- ❑ Microsand-assisted oxidation adsorption (Metclean™)
- ❑ Nanomaterials based adsorbents
- ❑ Hybrid selective adsorbents

There are reports that discuss bench- and pilot-scale testing of the above-listed technologies, but they generally suggest that these processes are not well understood and that further investigations are required (Sinha et al., 2001; Chowdhury et al., 2002b; Galeziewski et al., 2002; Smith and Edwards, 2002).

Centralized treatment is not always a feasible alternative, especially in areas where each home has a private well or where large-scale treatment costs are prohibitive. In these instances, point-of-use (POU) or point-of-entry (POE) treatments are often preferable. In general, they are easy to install and operate. Unfortunately, there is very little information available regarding the efficiency and operability of these systems. Among the most promising under-the-sink (POU) treatment alternatives for arsenic removal are AA and GFH (Kommineni et al., 2002). This report addresses AA and GFH but does not discuss them in the context of POU/POE applications.

4. TECHNOLOGY FEASIBILITY FOR NEW JERSEY

A review of the various arsenic removal technologies that have been proven to work in pilot- and full-scale studies is presented in Chapter 3. This chapter discusses the specific applicability of each technology for NJ systems. The arsenic removal technologies are reviewed in terms of their…

- ❑ Suitability for NJ waters
- ❑ Technology Status
- ❑ Arsenic removal efficiency
- ❑ Reliability (for consistently removing arsenic)
- ❑ Monitoring requirements
- ❑ Operational and maintenance requirements
- ❑ Residual handling and disposal issues
- ❑ Estimated costs

4.1. BACKGROUND WATER QUALITY

Tables 4-1 and 4-2 present the average water quality characteristics for the NJ water supplies that contain elevated levels of arsenic. Values for arsenic, alkalinity, hardness, pH, and sulfate were derived from the NJDEP Safe Drinking Water Act (SDWA) database. In other words, these results are specific to the systems listed in Tables 1-1 and 1-2. The data for iron, manganese, phosphate, silica, and total dissolved solids (TDS) were taken from U.S. Geological Survey (USGS) reports that address ground water quality in each of the five physiographic provinces of the state. As such, these numbers reflect the quality of both arsenic-containing and arsenic-free ground waters. The water chemistry summarized in Tables 4-1 and 4-2 does not disqualify any of the treatment techniques discussed in Chapter 3. In particular, the concentrations of background ions (e.g., phosphate, silica, sulfate) are (in most cases) well below the levels at which interference is likely.

Table 4-3 lists various water quality parameters that can impact the performance of arsenic treatment technologies. Concentration ranges relevant to NJ waters are displayed in the first

column. Notably, certain source waters in NJ exhibit sulfate concentrations in excess of 100 mg/L (Table 4-3) and this may preclude IX treatment at these locations. However, the other water quality parameters are all well within the operational limits for each technology. It is important to mention that RO treatment was not included in this analysis because of the inefficiencies and rigorous disposal requirements associated with this approach (see Section 4.7).

Table 4-1. Average Water Quality Characteristics for Impacted CWSs (As > 3 μg/L)

Water Quality Parameter	Valley & Ridge	Highlands	Piedmont	Inner Coastal Plain	Outer Coastal Plain
Arsenic (μg/L)	8.6	7.2	9.4	5.4	7.9
Alkalinity (mg/L as $CaCO_3$)	180	N/A	132	87	55
Chloride (mg/L)	34	N/A	57	19	30
Hardness (mg/L as $CaCO_3$)	175	N/A	236	102	51
pH	7.3	N/A	7.7	7.0	7.1
Sulfate (mg/L)	51	32	63	35	12
Iron (mg/L)	0.005	0.007	0.016	1	0.056
Manganese (mg/L)	0.006	0.002	0.011	0.077	0.018
Nitrate (mg/L)	0.28	0.19	0.41	0.6	3.1
Phosphate (mg/L)	<0.01	0.01	0.03	0.06	<0.01
Silica (mg/L)	11	22	24	9	8
TDS (mg/L)	314	135	313	136	45

N/A – not available

Table 4-2. Average Water Quality Characteristics for Impacted NCWSs (As > 3 µg/L)

Water Quality Parameter	Valley & Ridge	Highlands	Piedmont	Inner Coastal Plain	Outer Coastal Plain
Arsenic (µg/L)	11.0	8.2	7.8	10.1	8.1
Alkalinity (mg/L as CaCO$_3$)	N/A	N/A	138	80	65
Chloride (mg/L)	N/A	N/A	47	90	18
Hardness (mg/L as CaCO$_3$)	N/A	N/A	266	183	57
pH	N/A	N/A	7.3	6.9	7.0
Sulfate (mg/L)	37	92	118	16	12
Iron (mg/L)	0.005	0.007	0.016	1	0.056
Manganese (mg/L)	0.006	0.002	0.011	0.077	0.018
Nitrate (mg/L)	0.28	0.19	0.41	0.6	3.1
Phosphate (mg/L)	<0.01	0.01	0.03	0.06	<0.01
Silica (mg/L)	11	22	24	9	8
TDS (mg/L)	314	135	313	136	45

N/A – not available

Table 4-3. Impact of NJ Source Waters on Arsenic Treatment Technologies Performance

Source Water Quality Parameter	Ion Exchange	Activated Alumina Adsorption	Granular Ferric Hydroxide Adsorption	Coagulation-Assisted Media Filtration or Microfiltration
pH pH of the impacted systems in NJ varies between 4.4 and 8.4	Minimal or no effect	• Low pH (6.5 or less) is preferable • High pH (>7.5) can result in reduced run lengths • pH adjustment is necessary for waters with high pH	• Low pH (7.5 or less) is preferable • High pH (>8.0) can result in reduced run lengths • pH adjustment is necessary for waters with high pH (>8.0)	• pH is not a major factor • Low pH is preferable
Sulfate sulfate concentrations for the impacted systems in NJ vary between 1-1725 mg/L	• Strongly interferes with arsenic removal • Run lengths are a function of the sulfate concentration • Not suitable for waters with >100 mg/L of sulfate	Minimal or no impact	Minimal or no impact	Minimal or no impact
Nitrate nitrate concentrations for the impacted systems in NJ are all less than 6 mg/L	• Behaves similar to sulfate • Interferes with arsenic removal	Minimal or no impact	Minimal or no impact	Minimal or no impact

Table 4-3. Impact of NJ Source Waters on Arsenic Treatment Technologies Performance (continued)

Source Water Quality Parameter	Ion Exchange	Activated Alumina Adsorption	Granular Ferric Hydroxide Adsorption	Coagulation-Assisted Media Filtration or Microfiltration
Silica silica concentrations for the impacted systems in NJ vary between 8-24 mg/L	Minimal or no impact	• At concentrations >50 mg/L and in waters with high pH (>7.5) will compete with arsenic • Minimal or no impact at low (<50 mg/L) concentrations	• At concentrations >50 mg/L and in waters with high pH (>7.5) will compete with arsenic • Minimal or no impact at low (<50 mg/L) concentrations	• High silica concentrations (>50 mg/L) may foul the microfiltration membranes • No impact at low silica concentrations
Phosphate phosphate concentrations for the impacted systems in NJ vary between 0.01-0.06 mg/L	Minimal or no impact	Minimal or no impact	• Strongly impacts the run lengths for arsenic removal at high phosphate concentrations (>0.25 mg/L) • No impact at low concentrations (<0.25 mg/L)	Minimal or no impact
Iron iron concentrations for the impacted systems in NJ vary between 0.005-1.0 mg/L	• High concentrations • (>1 mg/L) of iron may plug the media • Oxidation for iron removal may be necessary for waters with high iron concentrations (>1 mg/L)	• High concentrations • (>1 mg/L) of iron may plug the media • Pre-oxidation for iron removal may be necessary for waters with high iron concentrations (>1 mg/L)	• High concentrations • (>1 mg/L) of iron may plug the media • Pre-oxidation for iron removal may be necessary for waters with high iron concentrations (>1 mg/L)	• Iron may enhance coagulation process and improve arsenic removal

Table 4-3. Impact of NJ Source Waters on Arsenic Treatment Technologies Performance (continued)

Source Water Quality Parameter	Ion Exchange	Activated Alumina Adsorption	Granular Ferric Hydroxide Adsorption	Coagulation-Assisted Media Filtration or Microfiltration
Manganese manganese concentrations for the impacted systems in NJ vary between 0.002-0.077 mg/L	• High concentrations (>0.5 mg/L) of manganese may plug the media • Oxidation for manganese removal may be necessary for waters with high manganese concentrations (>0.5 mg/L)	• High concentrations (>0.5 mg/L) of manganese may plug the media • Oxidation for manganese removal may be necessary for waters with high manganese concentrations (>0.5 mg/L)	• High concentrations (>0.5 mg/L) of manganese may plug the media • Oxidation for manganese removal may be necessary for waters with high manganese concentrations (>0.5 mg/L)	Minimal or no impact
TDS TDS for the impacted systems in NJ vary between 26-478 mg/L	Treatment efficiency is reduced if TDS concentration in the source water exceeds 2,000 mg/L	Minimal or no impact	Minimal or no impact	Minimal or no impact

4.2. ION EXCHANGE

IX systems that utilize strongly basic, anionic resins are a proven technology for arsenic removal. Previous studies indicate that IX processes can consistently and reliably reduce arsenic concentrations in groundwater to below 3 µg/L. Data (in graphical form) from several representative studies is included in Appendix C, and the accompanying summary reports (conference proceedings) can be found in Appendix D.

Arsenic removal via IX is generally not affected by varying pH in the range of 6.5 to 9. However, co-occurring solutes such as sulfates can significantly impact the IX performance. Pilot- and full-scale studies have shown that IX treatment may not be viable for waters with sulfate concentrations above 100 mg/L. There are only a few impacted systems in NJ with sulfate concentrations above 100 mg/L; meaning IX would be a feasible treatment alternative at most locations.

Nitrate is similar to sulfate in its effect on IX treatment. As indicated in Table 4-3, nitrate levels in NJ waters that contain arsenic are well below the corresponding sulfate concentrations, and so nitrate is not likely to impact IX treatment efficiency.

IX treatment can have significant operational requirements and may generate large quantities of liquid residuals if the media requires frequent regeneration. Also, intensive monitoring may necessary to detect chromatographic peaking (premature arsenic breakthrough) in areas where background ion concentrations are significant. For these reasons IX treatment, although a feasible alternative, may not be the best option for most NJ systems.

4.3. ACTIVATED ALUMINA ADSORPTION

AA adsorption is easy to implement and has proven to be an economical alternative for removing arsenic from groundwaters. Numerous studies, some of which are identified in Chapter 3, have demonstrated that AA treatment can consistently and reliably lower arsenic concentrations to below 3 µg/L. Data (in graphical form) from several representative studies is included in

Appendix C; the accompanying summary reports (conference proceedings) can be found in Appendix E.

The bed life of an AA system is a function of pH, where performance improves as pH decreases. The pH in most NJ waters (that contain arsenic) is fairly low, meaning that pH adjustment prior to AA treatment is probably not necessary. In those cases where pH adjustment is required, it can be achieved using acid or carbon dioxide. Regarding interferences, the most significant interfering contaminant for AA treatment is silica. Silica concentrations in NJ groundwater are generally below 50 mg/L, and these levels are not likely to affect AA performance.

If an AA system is operated in a disposable mode (to avoid using costly/hazardous regenerant solutions) it will generate both a liquid and a solid residual, namely backwash water and spent media. In general, spent AA media will pass TCLP tests and therefore not be classified as hazardous. The backwash water primarily contains suspended grit and sediment and does not have elevated levels of arsenic. Thus, it can simply be filtered and then processed along with the incoming raw water. In other words, an AA system can be arranged so it does not generate liquid wastes. As discussed elsewhere, this has important ramifications in NJ.

4.4. GRANULAR FERRIC HYDROXIDE ADSORPTION

Arsenic removal via GFH is currently being implemented in full-scale treatment plants throughout Germany and the United Kingdom. GFH treatment is also being utilized in the United States, where it can be purchased through US Filter. The NJ-American Water Company is currently pilot-testing GFH media for arsenic removal at its Race Street well, located in Frenchtown, NJ. The well has an average flow rate of 70 gpm and an arsenic concentration of 13 µg/L. A GFH system was chosen for this pilot test because it does generate wastewater (see below) and the spent GFH media will pass TCLP tests (and therefore not be classified as hazardous). A variety of sources (including the aforementioned pilot study) indicate that GFH systems can consistently and reliably lower arsenic concentrations to below 3 µg/L. Data (in graphical form) from several representative studies is included in Appendix C, and the accompanying summary reports (conference proceedings) can be found in Appendix F.

GFH performance increases with decreasing pH. Although some impacted waters in NJ exhibit a pH above 8.0 (sufficient to shorten GFH run lengths significantly), pH adjustment is not difficult or expensive to implement. The most important interfering contaminant for GFH treatment is phosphate. The phosphate concentrations in NJ waters are well below 0.25 mg/L, the threshold limit above which phosphate interference becomes considerable.

Like most adsorption process, GFH treatment is economical and easy to implement. Spent GFH media will usually pass TCLP tests and can therefore be disposed of in non-hazardous landfills. Furthermore, GFH treatment can be operated so it does not produce a wastewater stream (in the same fashion as for AA treatment) and thereby avoids potential conflicts with POTW effluent discharge limits and surface water quality standards.

4.5. COAGULATION/FILTRATION

CF processes can effectively lower arsenic concentrations to below 3 µg/L, and if the coagulation step is properly "tuned," this level of performance can be sustained. In general, higher coagulant dosages will yield higher arsenic removal rates, although pH adjustment is also important. Data illustrating the performance of coagulation-based systems is included in Appendix C, and the accompany summary reports can be found in Appendix G.

Unlike IX, AA and GFH, the CF process is relatively insensitive to co-occurring contaminants. Previous studies have shown that CF treatment is particularly effective for waters with high concentrations of interfering ions.

Coagulation/filtration processes will generate residuals (including a liquid waste stream) that may require some processing prior to disposal. As noted for other treatments that produce liquid residuals, the inability of a POTW to accept such a waste and still meet their effluent discharge limits (based on surface water quality standards) may render this technology infeasible. Even though the costs for large-scale CF may be higher than for adsorptive processes, it provides the added benefit of improved finished water quality (due to the filtration step). In addition, coagulation-assisted, high-rate media filtration systems are now available in packages suitable

for implementation at wellheads. For example, the FerriMet^{TM} system available through Hydroglobe recently underwent field tests in Hopewell, NJ, where it processed arsenic-laden groundwater for several days (at a rate of ~3 gpm) and consistently achieved effluent arsenic levels of below 5 µg/L (see Appendices C and G).

4.6.   COAGULATION/MICROFILTRATION

CMF is yet another proven technology for arsenic removal. As with the other technologies, previous research has demonstrated its capability to lower arsenic levels in drinking water to below 3 µg/L (see Appendices C and G).

As in the case of CF treatment, CMF is a useful approach to treating waters with high background concentrations of competing ions. Some of the larger NJ systems may choose CMF for the additional water quality benefits afforded by the membrane filtration step.

Backwash water from CMF processes can usually be discharged to a public sewer after the suspended solids have been removed. CMF treatment operations would require trained personnel and therefore may not be a feasible alternative for small CWSs and NCWSs (due to limited resources).

4.7.   TREATMENT TECHNOLOGY STRENGTHS AND WEAKNESSES

Table 4-4 summarizes the advantages and disadvantages of each of the four established arsenic treatment technologies that were considered most feasible for NJ waters. Each treatment technology has its own strengths and limitations. The advantages and disadvantages presented in this table are general in nature and not specific to NJ waters. We have purposely not eliminated advantages/disadvantages that would appear irrelevant based on the generalized NJ water quality data, as some systems fall outside this general range. The treatment technologies that have fewer drawbacks and more advantages are the ones that are likely to be selected by the impacted NJ CWSs and NCWSs. As science progresses, newer technologies will be developed that could be more efficient at removing arsenic than the ones that currently exist.

Table 4-4. Arsenic Treatment Technologies – Advantages and Disadvantages

Treatment Technology	Advantages	Disadvantages
Ion Exchange	• Established treatment for arsenic removal (NSF-certified resins available) • Performs well in a wide pH range (6.5-9.0), so pH adjustment is generally unnecessary • Applicable for small POU and POE systems • Available as packaged treatment systems for wellhead application	• Large volumes of sodium chloride salt solution are required for regeneration • Co-occurring solutes like sulfate and nitrate can significantly impact treatment performance • Achievable run lengths are a function of sulfate concentrations in the source waters • Labor- and chemical-intensive process • Monitoring for chromatographic peaking of arsenic is necessary • Large volumes of spent regenerant solution with relatively high concentrations (0.5-5 mg/L) of arsenic • Chemicals used to treat spent regenerant will produce sludge (disposal issue)

Table 4-4. Arsenic Treatment Technologies – Advantages and Disadvantages (continued)

Activated Alumina Adsorption	• Economical alternative • Simple to install and operate • A variety of media types/brands are available • Negligible water loss, less than one percent. • Can be used with or without on-site regeneration • If used without on-site regeneration, the only liquid waste stream is the backwash water that contains little or no arsenic (can be disposed of in a sewer or storm drain) • "Throwaway" mode of operation requires a minimal footprint • Available as package treatment systems • Applicable for small POU and POE systems • Minimal or no interference from TDS, sulfate and nitrate in source waters • Can also remove fluoride • NSF-certified media are available	• May require pre-and post- pH adjustment • High source water pH (>7.5) may reduce run lengths • Interference from co-occurring ions (i.e., silica) may reduce arsenic adsorption capacity • Regeneration may produce a liquid stream with high concentrations of arsenic and aluminum • Regenerated media exhibits a lower adsorption capacity than new media • For some systems, re-fluoridation of finished water may be required
Granular Ferric Hydroxide Adsorption	• Economical alternative • Simple to install and operate • Negligible water loss, less than one percent • pH adjustment not necessary if ambient pH < 8 • Longer run lengths and less operational attention than AA • Smaller footprints • Available as package treatment systems • Applicable for small POU and POE systems • Minimal or no interference from TDS, sulfate and nitrate • NSF-certified media are available	• High pH (>8.0) may reduce run lengths • May require pre-and post-pH adjustment • Presence of phosphate in source waters at concentrations above 0.25 mg/L can interfere with arsenic removal • Occasional release of iron fines into the finished water may occur • Needs frequent backwashing if the source water has lot of silt and debris

Table 4-4. Arsenic Treatment Technologies – Advantages and Disadvantages (continued)

Coagulation Filtration or Microfiltration	• Less interference from co-occurring ions • Provides additional benefit of filtration for turbidity or microbial removal; useful for low quality groundwaters or for groundwaters that are under the influence of surface water • Can be tailored to achieve any targeted arsenic removal by adjusting the coagulant dosage • Water loss from backwashing is low, between 2-5%; can be further minimized by using backwash water recovery systems • Available as fully-automated package treatment systems • Cost effective for large (i.e., 5 mgd or larger), centralized groundwater treatment facilities impacted by surface waters	• Installation and operation costs could be high • Coagulant must be compatible with the membrane or media • Backwash water will contain solids (floc particles) high in arsenic concentrations; may need some processing for solids separation • Backwash water loss of 2-5% could be too high for some locations

4.8.   RESIDUALS HANDLING AND DISPOSAL

All arsenic treatment technologies generate liquid and/or solid residuals, as discussed in Chapter 3. The residuals handling and disposal options will vary from technology to technology. For example, the backwash water from adsorption processes will be non-hazardous and may be blended back into the feed after cartridge or bag filtration. Alternatively, liquid wastes produced during regeneration in IX systems are likely to be characterized as hazardous unless a precipitation step is also included in the treatment process. Precipitation serves to bind the soluble arsenic into an insoluble precipitate. Reject streams from NF and RO will have elevated concentrations of arsenic and other salts. Disposal of liquid waste streams from arsenic treatment facilities to a public sewer will be regulated by local industrial pretreatment requirements. Solid wastes generated from coagulation processes or the exhausted adsorption media are likely to be characterized as non-hazardous materials and could be sent to non-hazardous landfills.

With increasingly stringent regulations governing the discharge and disposal of waste materials, residuals management is now a critical consideration in choosing an appropriate treatment technology. Table 4-5 summarizes the types of residuals produced by the various arsenic treatment technologies. It also includes possible disposal methods for the liquid and solid residuals generated by each process.

With regard to solid residuals, the appropriate disposal method is determined by the relative toxicity of the waste material. As indicated in the previous sections, many studies of arsenic technologies have not included toxicity testing of treatment residuals. Hence there is relatively little information on the matter. However, the limited work that has been completed appears to be promising. For example, Norton et al. (2001) and Chowdhury et al. (2002) have indicated that spent AA and GFH are not likely to exceed typical toxicity (TCLP) limits for municipal landfills. We also understand that the preliminary data from the NJ-American, Frenchtown study with GFH indicates that the spent media will pass the TCLP test for disposal without classification as a hazardous waste. In addition, during the NJCAT verification of the FerriMet

treatment system, it was determined that the ferric hydroxide sludge generated during this process contained 8,300 mg As/kg dry solids, a value below the standard for a hazardous waste.

Table 4-5. Summary of Arsenic Treatment Residuals Management and Disposal Methods

Treatment Technology	Form of Residual	Type of Residual	Possible Disposal Methods
Ion Exchange	Liquid	Spent Regeneration Stream	Sanitary Sewer Direct Discharge Evaporation Ponds
	Solid	Spent Resin	Landfill Hazardous Waste Landfill Return to Vendor
Activated Alumina Adsorption	Liquid	Backwash Water	Sanitary Sewer Direct Discharge Evaporation Ponds
	Solid	Spent Alumina	Landfill Hazardous Waste Landfill
Granular Ferric Hydroxide Adsorption	Liquid	Backwash Water	Sanitary Sewer Direct Discharge Evaporation Ponds
	Solid	Spent Media	Landfill Hazardous Waste Landfill
Coagulation/ Filtration	Liquid	Filter Backwash	Sanitary Sewer Direct Discharge Evaporation Ponds
	Solid	Sludge	Sanitary Sewer Land Application Landfill Hazardous Waste Landfill
Coagulation/ Microfiltration	Liquid	MF Backwash	Sanitary Sewer Direct Discharge Evaporation Ponds
	Solid	Sludge	Sanitary Sewer Land Application Landfill Hazardous Waste Landfill

The regulatory issues associated with liquid residuals may prove to be more challenging than those for solid wastes. Ultimately, whether liquid wastes are discharged directly to the environment or to a sanitary sewer, the Clean Water Act is a primary consideration. Direct discharge of pollutants to surface waters is prohibited except in compliance with a National

Pollutant Discharge Elimination System (NPDES) permit. It is conceivable that an NPDES permit would allow for the discharge of a liquid residual that contained arsenic. However, the limits identified in the permit would reflect state regulations concerning pollutant concentrations in surface waters. Notably, the regulated limit for arsenic in NJ waters is well below that of other states (Table 4-6). In fact, it is highly unlikely that an arsenic treatment system or a wastewater plant will generate discharge water that complies with this standard. For one thing, influent wastewater sometimes exhibits arsenic concentrations that are similar to levels in the local aquifer (especially in areas where aquifers are the primary source of drinking water). Since wastewater plants do not normally achieve significant arsenic removal, it may be that wastewater plants throughout NJ are currently generating treated effluent that exceeds the surface water standard for arsenic. Clearly, a problem arises when an arsenic treatment system discharges to a public sewer and the associated wastewater plant is then required to monitor for arsenic. As such, this issue must be carefully addressed before attempting to implement large-scale arsenic treatment efforts in NJ.

Table 4-6. Arsenic Standards for Surface Waters

State	Arsenic Standard (µg/L)
New Jersey	0.017
New York	25
Arizona	50

4.9.   ARSENIC TREATMENT SELECTION

Selection of the right treatment technology for arsenic removal for a specific water system should be based on careful consideration of many factors including:

- ❑ Water quality (pH, arsenic and co-occurring ion concentrations)
- ❑ System capacity
- ❑ Site constraints (availability of land, power and sewer connection)

❑ Residuals handling preferences

❑ Existing treatment system

❑ Qualitative decision drivers (ease of implementation, public acceptance)

❑ Costs

Smaller systems in NJ with less operator experience and fewer economical resources will likely choose arsenic treatment technologies that require less operational assistance and chemical addition such as the disposable adsorptive media (e.g., AA or GFH) processes. For many small utilities, disposable media may present the least cost option. Choosing an adsorptive media process with no (on-site) regeneration eliminates the need for the utility to handle hazardous chemicals that are used in regeneration and also eliminates complicated requirements for disposal of the spent regenerant solution. The achievable run lengths with the adsorptive media are a function of the water quality including feed water pH and the concentrations of interfering ions such as silica, fluoride and phosphate. Adjustment of pH may be necessary for waters with high pH. Secondary affects like pH reduction that result in higher TDS in the finished water must be considered for systems that currently are facing corrosion control or other water quality issues. Also, systems with high levels of co-occurring contaminants such as fluoride, silica, phosphate and chloride must consider the possible interferences of these ions with the adsorption processes. In addition to the spent media, adsorption processes also produces a small backwash water stream, as the media need to be occasionally backwashed to prevent excessive head loss development. Disposable media systems are simple to operate, have smaller footprint, and can be cost-effective. Proper pilot testing is necessary to understand the operational and design parameters and the impact of water quality on the achievable run lengths.

Larger systems in NJ with more experienced operators and greater resources are better suited for more complex treatment systems that include the use of hazardous chemicals for altering water quality during treatment (e.g., pH reduction to achieve greater adsorption capacity) or in the regeneration of spent media. These systems are also more likely to invest in technologies such as coagulation/filtration and are more prepared to deal with residuals from this type of treatment process. The larger systems typically have skilled staff to handle processes such as coagulation/filtration. In coagulation/filtration processes, ferric or alum coagulant is added to the

feed water and the coagulated water is filtered using high-rate media filters or low-pressure membrane filters such as MF or UF. These processes have the added benefits of turbidity removal and provide microbial barrier. Coagulation-assisted filtration processes can be cost-effective for centralized groundwater treatment, especially for source waters that contain a number of co-occurring, interfering ions.

For both small and large systems in NJ, the selection of an arsenic treatment process would be governed by site-specific factors like availability of land, sewer/storm drain access and neighborhood preferences. Each impacted CWS and NCWS can use the recommendations of this report as a general guidance. However, independent evaluations should be performed using site-specific constraints to identify the treatment technology most suitable for those conditions.

Table 4-7 compares the four most promising treatment technologies in terms of qualitative and quantitative selection drivers. The arsenic treatment technologies are ranked 1 through 4 for each decision driver (i.e., ease of implementation). The basis for the ranking of each parameter is shown in the right-most column. A higher rank (i.e., 4) indicates that the technology is more suitable for implementation. This type of analysis has to be performed for each impacted system, accounting for the utility preferences and site constraints. The analysis shown in Table 4-7 is purely for illustration purposes.

Table 4-7. Illustration of Arsenic Treatment Technology Ranking Based on Various Decision Drivers

Decision Driver	Ion Exchange	Activated Alumina Adsorption	Granular Ferric Hydroxide Adsorption	Coagulation Filtration or Microfiltration	Scoring Basis
Ease of Implementation	2	4	4	2	• High score for technologies that are easy to install and operate • Low score for cumbersome technologies
Labor Required	1	3	4	2	• High score for technologies that can be automated • Low score for labor-intensive technologies
Process Reliability	1	4	4	4	• High score for processes that have less interference from source water quality • Low score for processes that are highly impacted by Co-occurring ions
Mechanical Reliability	1	4	4	2	• High score for sturdier processes • Low score for processes with more moving parts
Positive System Water Quality Impacts	1	3	2	4	• High score for technologies that help in complying with other regulations • Low score for technologies that provide no additional benefit
Negative System Water Quality Impacts	1	3	3	4	• High score for processes that do not effect the water quality adversely • Low score for processes that may degrade the treated water quality
Public Acceptance	1	4	4	2	• High score for technologies that have minimal impact on the neighborhood • Low score for technologies that have lots of interference with neighborhood activities
Process Flexibility	1	3	3	4	• High score for processes that can be readily upgraded or modified • Low score for processes that are difficult to expand
Costs	1	4	4	2	• High score for low cost technologies • Low score for high cost technologies
Residuals Handling	1	4	4	1	• High score for technologies that produce little or no waste stream
Cumulative Score	**11**	**36**	**36**	**27**	• High scoring technologies are more preferable

4.10. ARSENIC TREATMENT COSTS

Malcolm Pirnie has developed a computerized tool that is capable of generating cost estimates for various arsenic treatment technologies. These estimates include values for initial capital investment as well as long-term operational/maintenance costs. Because the operation of many arsenic treatment systems is heavily influenced by background water quality, the tool requires detailed information on the chemical composition of the water(s) in question. In this report, five generic waters were developed for the purpose of generating cost estimates. Each of the waters listed represents a specific circumstance that applies to New Jersey.

- ❏ **NCWS (Low Arsenic):** represents an "average" non-community water supply with a low level of arsenic (low relative to other non-community supplies in New Jersey)

- ❏ **NCWS (High Arsenic):** represents an "average" non-community water supply with a high level of arsenic (high relative to other non-community supplies in New Jersey)

- ❏ **CWS (Low Arsenic):** represents an "average" community water supply with a low level of arsenic (low relative to other community supplies in New Jersey)

- ❏ **CWS (High Arsenic):** represents an "average" community water supply with a high level of arsenic (high relative to other community supplies in New Jersey)

- ❏ **CWS (Low Silica/TDS, Low Arsenic):** represents an "average" community supply with a low level of arsenic and low levels of silica and total dissolved solids

Again, these generic systems were designed to reflect some of the more common conditions (pertaining to arsenic-laden water supplies) found throughout New Jersey. The cost analyses for the generic impacted waters of Table 4-8 are shown in Table 4-9. It should be noted that these estimates were developed for a target effluent arsenic concentration of 3 µg/L, and that costs would be less if the target were 5 µg/L or 7 µg/L.

Notably, Table 4-9 indicates that AA is the least expensive alternative for NCWSs while GFH is the least expensive option for CWSs. The table clearly shows that this difference is linked to operations and maintenance (O&M) costs rather than capital expenses. Capital costs for these two treatments are relatively similar, but the associated O&M costs vary considerably. In

general, capital costs are defined by the system capacity and O&M costs are defined by water quality (i.e., media changeout frequency, backwash frequency, etc.). Simply put, the water quality defined for NCWSs favors AA treatment whereas the water quality defined for CWSs favors GFH treatment. Again, these generic water supplies are meant to represent average NCWSs and CWSs. In reality, there will undoubtedly be NCWSs that favor GFH and CWSs that favor AA. The table also shows the impact of silica and TDS on the operating costs associated for AA and GFH.

Table 4-8. Generic NJ Impacted Water Supplies Used in Cost Analysis

	NCWS Low Arsenic	NCWS High Arsenic	NCWS High Arsenic Low Flow	CWS Low Arsenic	CWS High Arsenic	CWS High Arsenic Low Flow	CWS Low Arsenic Low Silica/TDS
Design Capacity (mgd)	0.1	0.1	0.01	2.5	2.5	0.5	2.5
System Size	Large	Large	Small	Very Large	Very Large	Large	Very Large
Arsenic (µg/L)	7	15	15	7	15	15	7
Alkalinity (mg/L as CaCO$_3$)	120	120	120	110	110	110	110
Chloride (mg/L)	40.0	40.0	40.0	30.0	30.0	30.0	30.0
Hardness (mg/L as CaCO$_3$)	200	200	200	160	160	160	160
pH	7.2	7.2	7.2	7.5	7.5	7.5	7.5
Sulfate (mg/L)	65.0	65.0	65.0	35.0	35.0	35.0	35.0
Iron (mg/L)	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Manganese (mg/L)	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Phosphate (mg/L)	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Silica (mg/L)	25	25	25	25	25	25	8
TDS (mg/L)	300	300	300	300	300	300	65

Table 4-9.   Cost Evaluations for Generic Impacted Water Supplies of NJ (20-year amortization period, 7% interest rate used in calculating total cost)

Preferred Technologies	Capital Cost ($)	O&M Cost ($/1000 gal)	Total Cost ($/1000 gal)
NCWS (Low Arsenic)			
Disposable AA	143,000	0.50	0.87
Disposable GFH	158,000	1.45	1.86
CMF	1,010,000	4.05	6.66
IX	Not Feasible[*]	Not Feasible	Not Feasible
NCWS (High Arsenic)			
Disposable AA	143,000	1.02	1.39
Disposable GFH	157,000	3.10	3.51
CMF	1,010,000	4.05	6.66
IX	Not Feasible	Not Feasible	Not Feasible
NCWS (High Arsenic, Low Flow)			
Disposable AA	47,000	4.93	6.14
Disposable GFH	38,000	6.03	6.99
CMF	150,000	8.22	12.05
IX	Not Feasible	Not Feasible	Not Feasible
CWS (Low Arsenic)			
Disposable GFH	1,420,000	0.19	0.34
Disposable AA	1,510,000	0.38	0.54
CMF	4,790,000	0.74	1.23
IX	989,000	0.21	0.31
CWS (High Arsenic)			
Disposable GFH	1,420,000	0.40	0.54
Disposable AA	1,510,000	0.77	0.93
CMF	4,790,000	0.74	1.23
IX	989,000	0.21	0.31
CWS (High Arsenic, Low Flow)			
Disposable GFH	360,000	0.73	0.92
Disposable AA	428,000	0.79	1.01
CMF	2,130,000	1.28	2.37
IX	570,000	0.24	0.53
CWS (Low Silica/TDS, Low Arsenic)			
Disposable GFH	1,290,000	0.17	0.31
Disposable AA	1,380,000	0.34	0.49
CMF	4,520,000	0.69	1.16
IX	943,000	0.19	0.29

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[*] IX treatment is not cost-effective at high sulfate concentrations (> 50 mg/L)

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APPENDIX A

**COMMUNITY WATER SUPPLIES IN NEW JERSEY WITH ARSENIC LEVELS
GREATER THAN OR EQUAL TO 3 PARTS PER BILLION**

[*average data for aquifers in the region where system is located - values in parentheses correspond to 25th and 75th percentiles]

PWID	System Name	Municipality	Physiographic Province	Design Capacity (mgd)	System Size	Arsenic (ug/L)	Alkalinity (mg/L as CaCO3)	Chloride (mg/L)	Hardness (mg/L as CaCO3)	pH	Sulfate (mg/L)	Iron* (mg/L)	Manganese* (mg/L)	Nitrate* (mg/L)	Phosphate* (mg/L)	Silica* (mg/L)	TDS* (mg/L)
1105001	HOPEWELL BORO W DEPT	Hopewell Boro	Piedmont	0.50	Very Large	25.1	124	16.3	278	7.9	132.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1107002	LAWRENCEVILLE W CO	Lawrence Twp.	Piedmont	1.8	Very Large	23	49	82.2	185	6.8	58.1	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0811003	COLONIAL ESTATES	Monroe Twp.	Valley and Ridge	0.70	Very Large	14	153	16.7	10	6.8	16.1	0.005 (ND-0.019)	0.005 (ND-0.041)	0.28 (ND-5.6)	<0.01	11 (9.4-14)	314 (132-320)
1526001	SEASIDE HEIGHTS WATER DE	Seaside Heights Boro	Outer Coastal Plain	4.5	Very Large	14	86	276.0	182	8.2	49.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
0233001	MAHWAH WATER DEPARTMENT	Mahwah Twp.	Piedmont	8.9	Very Large	12.4	130	59.3	220	7.7	42.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1520001	OCEAN TWP MUA PEBBLE BEA	Ocean Twp.	Outer Coastal Plain	1.5	Very Large	11.5	27	8.0	40	7.1	9.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
0140001	BELLMAWR WATER DEPT	Bellmawr Boro	Inner Coastal Plain	6.2	Very Large	9.9	116	23.2	124	7.4	22.4	1	0.077	0.6 (ND-198)	0.06	9.1	136
0248001	RAMSEY WATER DEPT	Ramsey Boro	Piedmont	4.3	Very Large	8.4	128	77.4	224	7.4	31.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0713001	MONTCLAIR WATER BUREAU	Montclair Town	Piedmont	6.5	Very Large	8	110	98.7	270	7.9	41.1	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1702001	ELMER BORO W DEPT	Elmer Boro	Outer Coastal Plain	1.2	Very Large	7.2	161	7.9	23	7.9	8.5	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1009001	FLEMINGTON WATER DEPARTMENT	Flemington Boro	Piedmont	1.5	Very Large	7.2	160	58.0	309	7.9	116.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0264001	WALDWICK WATER DEPT	Waldwick Boro	Piedmont	3.2	Very Large	7						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1005001	CLINTON TOWN W DEPT	Clinton Town	Highlands	2.0	Very Large	6.4						0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (ND-0.02)	22 (19-29)	135 (105-185)
0201001	ALLENDALE WATER DEPT	Allendale Boro	Piedmont	1.0	Very Large	6	142	76.1	224	7.9	24.1	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
2004002	ELIZABETHTOWN WATER CO	Elizabeth City	Piedmont	199.7	Very Large	6	131	40.2	351	7.6	230.5	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0228001	HO HO KUS WATER DEPT	Hohokus Boro	Piedmont	1.9	Very Large	6	147	148.9	227	8.2	16.2	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0115001	LONGPORT WATER DEPARTMENT	Longport Boro	Outer Coastal Plain	2.7	Very Large	6	64	6.3	33	6.7	11.7	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
0811002	MONROE TWP MUA	Monroe Twp.	Valley and Ridge	4.0	Very Large	6	32	9.9	13	7.0	8.1	0.005 (ND-0.019)	0.006 (ND-0.041)	0.28 (ND-5.6)	<0.01	11 (9.4-14)	314 (132-320)
1108001	PENNINGTON W DEPT	Pennington Boro	Piedmont	0.72	Very Large	6	147	35.2	211	6.9	30.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0251001	RIDGEWOOD WATER DEPT	Ridgewood Twp.	Piedmont	19.0	Very Large	5.5	180	91.7	278	7.9	69.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0329002	PEMBERTON TWP DEPT MAIN	Pemberton Twp.	Outer Coastal Plain	1.9	Very Large	5.3	93	2.2	82	7.7	2.1	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1532002	TUCKERTON WATER & SEWER DEPT	Tuckerton Boro	Inner Coastal Plain	1.4	Very Large	5	33	5.8	49	7.3	12.7	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1225001	MIDDLESEX W CO	Woodbridge Twp.	Inner Coastal Plain	49.0	Very Large	5	167	35.2	311	7.9	116.9	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	46 (26-102)
1914002	MONTAGUE WATER CO.	Montague Twp.	Valley and Ridge	1.1	Very Large	4	150	6.7	264	8.0	123.0	0.006 (ND-0.019)	0.006 (ND-0.041)	0.28 (ND-5.6)	0.06	11 (9.4-14)	314 (132-320)
0329001	MOUNT HOLLY WATER COMPANY	Mount Holly Twp.	Inner Coastal Plain	9.3	Very Large	4	76	3.0	79	7.3	15.8	1	0.077	0.6 (ND-198)	<0.01	9.1	136
0327001	NJ AMERICAN W CO WESTERN DIV	Pathryca Boro	Inner Coastal Plain	17.2	Very Large	4	64	20.0	58	7.6	21.1	1	0.077	0.6 (ND-198)	0.06	9.1	136
0832001	WEST DEPTFORD TWP WATER DEPT	West Deptford Twp.	Inner Coastal Plain	1.2	Very Large	4	92	30.7	36	7.4	30.6	1	0.077	0.6 (ND-198)	0.06	9.1	136
1011001	FRENCHTOWN WATER DEPARTMENT	Frenchtown Boro	Piedmont	0.27	Large	15.8	114	0.2	212	8.0	48.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1511010	NAVAL AIR ENG.STATION LAKEHRS	Jackson Twp.	Outer Coastal Plain	0.42	Large	10.5	40	22.0	28	8.2	9.5	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
0333004	VINCENTOWN WATER COMPANY	Southampton Twp.	Outer Coastal Plain	0.44	Large	10	88	3.2	72	7.9	6.6	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1920001	STILLWATER WATER DISTRIC	Stillwater Twp.	Valley and Ridge	0.38	Large	10					69.0	0.005 (ND-0.019)	0.006 (ND-0.041)	0.28 (ND-5.6)	<0.01	11 (9.4-14)	314 (132-320)
1911005	HARDYSTON TWP MUA INDIAN FIELD	Hardyston Twp.	Valley and Ridge	0.43	Large	9	386	103.0	392	7.2	39.7	0.005 (ND-0.019)	0.006 (ND-0.041)	0.28 (ND-5.6)	<0.01	11 (9.4-14)	314 (132-320)
1817001	ROCKY HILL W DEPT	Rocky Hill Boro	Piedmont	0.25	Large	8	111	7.0	154	8.0	40.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1922008	VERNON W CO	Vernon Twp.	Highlands	0.29	Large	8					32.1	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (ND-0.02)	22 (19-29)	135 (105-185)
0335001	ALLENWOOD MOBILE ESTATES	Tabernacle Twp.	Outer Coastal Plain	0.29	Large	6.3	104	1.0	66	8.0	14.3	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1020001	MILFORD W DEPT	Milford Boro	Piedmont	0.47	Large	5.3	129	55.2	207	7.4	95.2	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0332002	OAKVIEW LEISURE VILLAGE	Shamong Twp.	Inner Coastal Plain	0.29	Large	5.3	4	2.9	4	4.4	2.1	1	0.077	0.6 (ND-198)	0.06	9.1	136
0233005	BOGER'S RANCH ESTATES IN	Mahwah Twp.	Piedmont	0.27	Large	5	126	24.1	180	7.8	16.4	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0108004	NORRIS DALE MOBILE HOME PARK	Egg Harbor Twp.	Outer Coastal Plain	0.14	Large	4	6	7.5	12	6.2	12.2	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
0108003	SAGE INVESTMENT CORPORATION	Egg Harbor Twp.	Outer Coastal Plain	0.13	Large	3.8	7	15.8	7	5.0	1.8	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1511009	PLEASANT GARDENS APARTMENTS	Jackson Twp.	Outer Coastal Plain	0.01	Small	10	12	23.5	5	7.0	5.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1007002	ROSEMONT WATER DEPARTMENT	Delaware Twp.	Piedmont	0.04	Small	4.5	177	35.7	244	7.7	19.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1511017	JACKSON COLONIAL ARMS AP	Jackson Twp.	Outer Coastal Plain			10	46	5.0	68	7.2	7.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)
1352004	GARDEN STATE MOBIL HOME	Wall Twp.	Outer Coastal Plain			7.5	2	31.4	43	5.0	13.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (ND-0.1)	7.9 (6.3-10)	45 (26-102)

Region	%
Valley and Ridge	11.6%
Highlands	4.7%
Piedmont	39.5%
Inner Coastal Plain	14.0%
Outer Coastal Plain	30.2%

	Alkalinity	Chloride	Hardness	pH	Sulfate
median values	110.5	22.6	139.0	7.6	21.7
average values	102.9	39.3	144.9	7.3	39.8

APPENDIX B

**NON-TRANSIENT, NON-COMMUNITY WATER SUPPLIES IN NEW JERSEY WITH
ARSENIC LEVELS GREATER THAN OR EQUAL TO THREE PARTS PER BILLION**

Non-Community Water Systems

(*average data for aquifers in the region where system is located - values in parentheses correspond to 25th and 75th percentiles)

PWID	System Name	Municipality	Physiographic Province	Design Capacity (mgd)	System Size	Arsenic (ug/L)	Alkalinity (mg/L as)	Chloride (mg/L)	Hardness (mg/L as)	pH	Sulfate (mg/L)	Iron* (mg/L)	Manganese* (mg/L)	Nitrite* (mg/L)	Phosphate* (mg/L)	Silica* (mg/L)	TDS* (mg/L)
0613305	SEABROOK BROTHERS AND SO	Upper Deerfield Twp.	Outer Coastal Plain	4.4	Very Large	15	5	18.5	46	4.6	24.5	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1813303	3M MINING COMPANY	Montgomery Twp.	Piedmont	0.54	Very Large	10	150	14.0	190	8.0	48.0	0.016 (ND-0.26)	0.011 (ND-0.26)	3.1 (ND-19)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1922306	LEGENDS RESORT & CONFERENCE	Vernon Twp.	Highlands	1.4	Very Large	7						0.007 (0.004-0.011)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	136 (105-185)
0809301	FERRO CORPORATION	Logan Twp.	Piedmont	2.7	Very Large	5.6						0.016 (ND-0.26)	0.011 (ND-0.26)	3.1 (ND-19)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0807301	EL DUPONT DENIMOURS & CO	Greenwich Twp.	Outer Coastal Plain	1.3	Very Large	4.9	66	96.0	62	6.8	26.5	0.056 (0.016-0.2)	0.018 (0.010-0.036)	1.6 (ND-5.5)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1020300	CURTIS SPECIALTY PAPERS	Milford Boro	Piedmont	0.91	Very Large	4	130	133.0	169	7.2	27.2	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	7.9 (6.3-10)	313 (217-478)
1511303	LAKEHURST NAVAL AIR ENG.	Jackson Twp.	Outer Coastal Plain	0.63	Very Large	4						0.056 (0.016-0.2)	0.018 (0.010-0.036)	1.6 (ND-5.5)	0.03 (0.03-0.1)	7.9 (6.3-10)	45 (26-102)
0613301	CUMBERLAND REGIONAL HIGH	Upper Deerfield Twp.	Outer Coastal Plain	0.30	Large	12		5.6			6.6	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1021309	US BRONZE POWDERS	Raritan Twp.	Piedmont	0.29	Large	5.9	134	5.6	990	7.4	977.5	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	0.03 (0.03-0.1)	7.9 (6.3-10)	313 (217-478)
1021308	BARLEY SHEAF SCHOOL	Raritan Twp.	Piedmont	0.34	Large	3.9					14.1	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1612301	LITTLE SISTERS OF THE POOR	Totowa Boro	Piedmont	0.09	Medium	16	92	30.8	180	7.8	37.9	0.056 (0.016-0.2)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0613307	SEABROOK HOUSE	Upper Deerfield Twp.	Outer Coastal Plain	0.0005	Small	11	5	12.0	82	5.0	1.6	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1001301	VALLEY VIEW MANOR	Alexandria Twp.	Inner Coastal Plain	0.02	Small	9.6						—	0.077	0.6 (ND-198)	0.06	9.1	136
1016302	QUALITY PARTITION MFG	Kingwood Twp.	Inner Coastal Plain	0.03	Small	6	242	11.9	22	7.2	13.7	0.016 (ND-0.26)	0.018 (0.010-0.034)	0.6 (ND-198)	0.06	9.1	136
1413311	HARDING TOWNSHIP	Harding Twp.	Piedmont			23	103	27.0	976	7.5	1159.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1704302	LOWER ALLOWAYS CREEK SCH	Lower Alloways Cr.	Outer Coastal Plain			22	200	40.9	0	8.3	10.7	0.056 (0.016-0.2)	0.018 (0.010-0.034)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0613261	WOODLAND COUNTRY DAY SCH	Stow Creek Twp.	Inner Coastal Plain			21	150	1.6	77	7.7	1.6	0.016 (ND-0.26)	0.007 (ND-0.011)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
0315301	FOUNTAIN OF LIFE CENTER	Florence Twp.	Inner Coastal Plain			21						—	0.077	0.6 (ND-198)	0.06	9.1	136
2226500	HAWORTH SWIM CLUB	Haworth Boro	Piedmont			19.5						—	0.077	0.6 (ND-198)	0.06	9.1	136
1106394	TODDLER VILLAGE @ STONY BROOK	Hopewell Twp.	Piedmont			18					27.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106355	KOOLTRONIC, INC.	Hopewell Twp.	Piedmont			17					41.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0233316	MAHWAH BPOE	Mahwah Twp.	Piedmont			17					32.5	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1008301	EAST AMWELL IWP	East Amwell Twp.	Piedmont			17					23.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1805323	WILSON COLOR - R & D WEL	Branchburg Twp.	Piedmont			16					23.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1910316	SALERNO DUANE OF SUSSEX INC	Hampton Twp.	Highlands			15.7	135	16.8	196	6.7	260.0	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	136 (105-185)
1805386	WILSON COLOR - MAIN WELL	Branchburg Twp.	Piedmont			15						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1017301	PHILLIPS BARBER HEALTH	Lambertville City	Piedmont			14.6	134	33.6	170	6.7	39.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0263310	BREEN COLOR	West Amwell Twp.	Piedmont			14	43	13.1	130	7.9	32.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1316322	SATURN OF FREEHOLD	Freehold Twp.	Inner Coastal Plain			13.6					24.9	—	0.077	0.6 (ND-198)	0.06	9.1	136
1106376	PENNINGTON OFFICE PARK-A	Hopewell Twp.	Piedmont			13					18.2	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1805322	AMI	Branchburg Twp.	Piedmont			13					731.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1808316	HIGH ROAD CAREER CENTER	Franklin Twp.	Highlands			12.5					83.0	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	136 (105-185)
1016317	ARC//HUNTERDON ADULT TRAI	Kingwood Twp.	Piedmont			12.3					19.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1813318	WALDORF SCHOOL OF PRINCE	Montgomery Twp.	Piedmont			12					168.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0723304	THE MANOR	West Orange Town	Piedmont			12	55	19.1	97	7.6	2.1	0.005 (ND-0.019)	0.006 (ND-0.041)	0.6 (ND-198)	<0.01	11 (9.4-14)	314 (132-320)
1710301	ARTHUR P SCHALICK HIGH S	Pittsgrove Twp.	Valley and Ridge			12						0.007 (0.004-0.018)	0.002 (ND-0.011)	0.28 (ND-5.6)	0.01 (<0.01-0.02)	22 (19-29)	135 (105-185)
0811311	GLOUCESTER CO DAY TRAINI	Monroe Twp.	Piedmont			12					37.0	0.016 (ND-0.26)	0.011 (ND-0.26)	3.1 (ND-19)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1808318	HIGH ROAD UPPER SCHOOL	Franklin Twp.	Highlands			11.5	154	802.0	974	7.5	37.8	0.006 (ND-0.019)	0.006 (ND-0.041)	0.28 (ND-5.6)	0.01 (<0.01-0.02)	24 (19-34)	135 (105-185)
1024316	ESC SHCOOL	Tewksbury Twp.	Inner Coastal Plain			11.5	142	15.0	261	7.1	92.8	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	<0.01 (<0.01-0.02)	22 (19-29)	135 (105-185)
1810309	WOODFERN SCHOOL	Hillsborough Twp.	Piedmont			11.3	154	64.0	209	7.1	34.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1107304	LAWRENCE DAY SCHOOL	Lawrence Twp.	Piedmont			11.3					38.0	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	<0.01 (<0.01-0.02)	24 (19-34)	313 (217-478)
1922382	DISCOVERY YEARS	Vernon Twp.	Highlands			11						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	22 (19-29)	136 (105-185)
0263314	HUNTERDON HILLS PLAYHOUSE	Union Twp.	Highlands			11	97	49.0	164	7.2	12.9	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1217300	HARRIS STRUCTURAL STL CO	Piscataway Twp.	Piedmont			11	127	46.5	282	7.1	13.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.01 (<0.01-0.02)	24 (19-34)	313 (217-478)
2113322	TRUCKSTOPS OF AMERICA	Knowlton Twp.	Valley and Ridge			10						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	314 (132-320)
1016321	DEL RILO'S DELI & BAKE SHOPPE	Kingwood Twp.	Valley and Ridge			10					37.0	0.005 (ND-0.041)	0.006 (ND-0.041)	0.28 (ND-5.6)	<0.01	11 (9.4-14)	314 (132-320)
1511338	JACKSON MEMORIAL HIGH SC	Jackson Twp.	Piedmont			10	104	2.0	112	8.3	51.0	0.016 (ND-0.26)	0.011 (ND-0.26)	3.1 (ND-19)	-0.01 (<0.01-0.1)	24 (19-34)	313 (217-478)
1505365	OCEAN COUNTY UTILITIES A	Berkeley Twp.	Outer Coastal Plain			9.6					6.4	0.056 (0.016-0.2)	0.056 (0.016-0.2)	7.9 (6.3-10)	7.9 (6.3-10)	7.9 (6.3-10)	7.9 (6.3-10)
1001303	DELAWARE VALLEY REGIONAL	Alexandria Twp.	Piedmont			9.5	100	20.4	160	6.4	16.6	0.016 (0.016-0.2)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1108301	THE PENNINGTON SCHOOL	Pennington Boro	Inner Coastal Plain			9.2	130	31.0	187	7.0	27.4	0.007 (0.004-0.018)	0.007 (0.004-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	7.9 (6.3-10)	135 (105-185)
1808358	OAK CREST COUNTRY DAY SCHOOL	Franklin Twp.	Piedmont			9.2	156	34.9	114	7.5	259.0	0.016 (ND-0.26)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	136 (105-185)
1813301	PRINCETON ELKS 2129	Montgomery Twp.	Highlands			9.1	116	24.4	140	8.0	31.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1001300	LESTER D WILSON SCHOOL	Alexandria Twp.	Piedmont			9					28.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1614300	PASSAIC COUNTY GOLF COUR	Wayne Twp.	Inner Coastal Plain			9						0.016 (ND-0.26)	0.011 (ND-0.26)	0.6 (ND-198)	0.03 (0.03-0.1)	24 (19-34)	136
1022363	BISHOP & BISHOP (WELL #2	Readington Twp.	Piedmont			9	139	23.0	614	6.9	477.0	0.007 (0.004-0.018)	0.006 (ND-0.011)	0.28 (ND-5.6)	<0.01 (<0.01-0.1)	11 (9.4-14)	314 (132-320)
1710323	B & B POULTRY CO., INC.	Pittsgrove Twp.	Valley and Ridge			9	15	6.7	16	4.8	4.9	0.005 (ND-0.019)	0.006 (ND-0.041)	0.28 (ND-5.6)	<0.01 (<0.01-0.1)	24 (19-34)	314 (132-320)
1422315	TEDDY & ME DAYCARE	Morris Twp.	Piedmont			9					47.0	0.007 (0.004-0.018)	0.002 (ND-0.011)	3.1 (ND-19)	-0.01	24 (19-34)	45 (26-102)
1106320	BRISTOL MYERS, SQUIBB CO WELL	Hopewell Twp.	Outer Coastal Plain			9					61.4	0.016 (ND-0.26)	0.011 (ND-0.26)	0.6 (ND-198)	-0.01 (<0.01-0.1)	7.9 (6.3-10)	135 (105-185)
1413322	COUNTRY MILE VILLAGE	Harding Twp.	Piedmont			8.5						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	22 (19-29)	313 (217-478)
0410300	SIMSY'S PUB	Chesilhurst Boro	Inner Coastal Plain			8.5	3	5.3	8	5.7	1.0	0.056 (0.016-0.2)	0.077	3.1 (ND-19)	-0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1025307	UNION TWP SCHOOL	Union Twp.	Piedmont			8.5	113	17.0	4	7.2	10.6	0.016 (ND-0.26)	0.011 (ND-0.26)	3.1 (ND-19)	0.03 (0.03-0.1)	22 (19-29)	135 (105-185)
0603302	PINELAND LEARNING CENTER	Deerfield Twp.	Outer Coastal Plain			8.5	45	4.0	4	7.1	2.5	0.056 (0.016-0.2)	0.018 (0.010-0.036)	1.6 (ND-5.5)	-0.01 (<0.01-0.1)	7.9 (6.3-10)	135 (105-185)
1805389	WILSON COLOR-ADMIN. WELL	Branchburg Twp.	Piedmont			8.3						0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	-0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
0338300	INDUCTOTHERM CORP	Willingboro Twp.	Inner Coastal Plain			8	68	0.5	114	7.0	23.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1614313	PASSAIC COUNTY GOLF COURSE	Wayne Twp.	Piedmont			8	70	18.0	78	8.4	59.2	0.016 (ND-0.26)	0.077	1.6 (ND-5.5)	0.03 (0.03-0.1)	9.1	313 (217-478)
0263300	ROBERT D REYNOLDS SCHOOL	Upper Saddle River	Piedmont			8					24.5	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)

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Non-Community Water Systems

[*average data for aquifers in the region where system is located - values in parentheses correspond to 25th and 75th percentiles]

| PWID	System Name	Municipality	Physiographic Province	Design Capacity (mgd)	System Size	Arsenic (ug/L)	Alkalinity (mg/L as)	Chloride (mg/L)	Hardness (mg/L as)	pH	Sulfate (mg/L)	Iron* (mg/L)	Manganese* (mg/L)	Nitrate* (mg/L)	Phosphate* (mg/L)	Silica* (mg/L)	TDS* (mg/L)
1530372	MING DYNASTY BUFFET	Stafford Twp.	Outer Coastal Plain			8						0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
0816300	HARRISONVILLE SCHOOL	South Harrison Twp.	Piedmont			8	160	30.0	11	7.9	27.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021414	JAMES TOYOTA	Raritan Twp.	Piedmont			8	36	4.5	22	8.1	23.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1511330	NAVAL AIR ENG CTR/WELL 4	Jackson Twp.	Outer Coastal Plain			8	132	6.5	161	7.5	3.6	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1319326	GPU ENERGY	Howell Twp.	Outer Coastal Plain			8					9.7	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1106315	TOWNSEND PROPERTY TRUST L P	Hopewell Twp.	Piedmont			8					23.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1910313	CONDIT FORD	Hampton Twp.	Highlands			7.5					49.8	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	135 (105-185)
1810346	RCN RESIDENTIAL COMM. NETWORK	Hillsborough Twp.	Piedmont			7.3	109	4.5	426	7.5	325.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1108305	84 COMPONENTS	Pennington Boro	Piedmont			7.2						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1008300	ALBERT ELIAS RESIDENTIAL GROUP	East Amwell Twp.	Piedmont			7						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1107300	EDUCATIONAL TESTING SERV	Lawrence Twp.	Piedmont			7						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021333	TEKNIPLEX INC	Raritan Twp.	Piedmont			7	151	41.2	183	7.6	25.5	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021411	B & T DEVELOPMENT	Raritan Twp.	Piedmont			7	152	98.0	126	7.1	170.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0609301	MAUR RIV TWP BD OF ED LE	Maurice River Twp.	Outer Coastal Plain			7						0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1106308	STAGE DEPOT	Hopewell Twp.	Piedmont			7						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106353	PENN PARTNERSHIP PARSONS	Hopewell Twp.	Piedmont			7	155					0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106368	STAGE II MOTEL & PROF BL	Hopewell Twp.	Piedmont			6.8		101.0	400	7.5	48.4	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0808307	GIANT STEPS NURSERY SCHOO	Harrison Twp.	Piedmont			6.6						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1805327	TRANSCONTINENTAL GAS PIPELINE	Branchburg Twp.	Piedmont			6		15.1	0	7.2	41.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021998	FLEMINGTON CIRCLE BUICK	Raritan Twp.	Piedmont			6					28.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0435375	WATERFORD ELEMENTARY	Waterford Twp.	Outer Coastal Plain			6						0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1025322	POWERCO	Union Twp.	Piedmont			6						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1500303	OCEAN COUNTY UTILITIES A	Stafford Twp.	Outer Coastal Plain			6	53	26.0	4	7.0	36.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1022306	THREE BRIDGES SCHOOL	Readington Twp.	Piedmont			6	120	24.0	213	7.3	5.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022310	SALEM INDUSTRIAL PARK	Readington Twp.	Piedmont			6	152	29.5	248	6.5	38.2	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022342	READINGTON MUN	Readington Twp.	Piedmont			6	102	11.5	154	7.3	67.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022361	SALEM SQUARE	Readington Twp.	Piedmont			6	185	64.0	307	7.0	20.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022373	HEALTH PRODUCTS RESEARCH	Raritan Twp.	Piedmont			6	89	49.5	344	7.1	32.6	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021347	YALE MATERIALS HNDLING	Raritan Twp.	Piedmont			6	131	182.0	396	7.2	213.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021404	CENTER FOR ED ADV (FURN.	Raritan Twp.	Piedmont			6	143	23.8	344	7.3	39.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021419	VILLAGE MONTESSORI SCHOOL	Raritan Twp.	Piedmont			6	68	22.0	72	7.4	202.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0320347	OLDE TOWNE SQ CONDO ASSOC. INC	Medford Twp.	Outer Coastal Plain			6	224	19.0	270	7.5	39.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1810329	CHILDRENS WORKSHOP	Hillsborough Twp.	Piedmont			5.9					14.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1010311	CROSS ROADS CHRISTIAN ACADEMY	Franklin Twp.	Highlands			5.5	20	4.9	4	6.6	16.6	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	135 (105-185)
0103350	SOUTH JERSEY GAS CO	Egg Harbor Twp.	Outer Coastal Plain			5.3						0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1309323	FIRST FIDELITY BANK OFF.	Colts Neck Twp.	Outer Coastal Plain			5.3	163	191.5	25	6.8	4.9	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
0809311	LOGAN GENERATING PLANT	Logan Twp.				5					5.0						
1810335	HILLSBOROUGH & THREE BRIDGES R	Hillsborough Twp.	Piedmont			5					2.6	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022305	DARTS MILL DAY CARE CENT	Readington Twp.	Piedmont			5					3.6	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106352	CAMELOT NURSERY SCHOOL	Hopewell Twp.	Piedmont			5						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0436456	GARVEY CONVEYERS	Jackson Twp.	Outer Coastal Plain			5						0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1351309	ALLENTOWN CACING EQUIPME	Upper Freehold Twp.	Outer Coastal Plain			5					2.6	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1022337	QUICK CHECK CORP	Freehold Twp.	Inner Coastal Plain			5					5.0	1	0.077	0.6 (ND-198)	0.06	9.1	136
1022338	READINGTON FARMS	Readington Twp.	Piedmont			5	111	31.8	277	7.1	133.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022341	LANECO OF WHITEHOUSE	Readington Twp.	Piedmont			4.9	72	47.0	152	7.2	2.6	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021371	HUNTERDON COUNTY DEMOCRA	Readington Twp.	Piedmont			4.8	124	172.0	461	7.3	144.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021386	SPEEDWAY PLAZA / W. HORV	Raritan Twp.	Piedmont			4.5	201	123.0	339	7.2	43.4	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1511339	SWITLIK ELEMENTARY SCHOO	Jackson Twp.	Outer Coastal Plain			4.4	96	2.0	108	8.2	4.3	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1511341b	JACKSON OUTLET VILLAGE	Jackson Twp.	Outer Coastal Plain			4.4					5.1	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1810344	APPLIED WATER MANAGEMENT	Hillsborough Twp.	Outer Coastal Plain			4.3					5.0	0.056 (0.016-0.2)	0.018 (0.010-0.036)	3.1 (ND-19)	<0.01 (<0.01-0.1)	7.9 (6.3-10)	45 (26-102)
1318325	IRWIN LINCOLN MERCURY CA	Freehold Twp.	Inner Coastal Plain			4.2		7.2	750	7.8	622.0	1	0.077	0.6 (ND-198)	0.06	9.1	136
1021375	HUNTERDON MED CTR-WELL #	Raritan Twp.	Piedmont			4.2	190	93.2	346	7.4	59.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1107323	CHILDREN'S EXPRESS	Lawrence Twp.	Piedmont			4.2						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021378	IMONT PRE-SCH CNT	Raritan Twp.	Piedmont			4						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106319	PENNINGTON SHOP-RITE	Hopewell Twp.	Piedmont			4					47.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1005342	CLINTON TWP. MUNIC. BLDG.	Clinton Twp.	Highlands			4					36.2	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	135 (105-185)
1106358	PENNINGTON HAPPY SCHOOL	Hopewell Twp.	Piedmont			4					11.4	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0001308	ALEXANDRIA MIDDLE SCHOOL	Alexandria Twp.	Inner Coastal Plain			4	100	9.7	120	7.4	12.1	1	0.077	0.6 (ND-198)	0.06	9.1	136
1106357	HOPEWELL MUNIC SERVICES	Hopewell Twp.	Piedmont			4						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1820307	WATCHUNG HILL HIGH SCHOOL	Warren Twp.	Highlands			4					39.0	0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	135 (105-185)
1025327	P JAX INC	Union Twp.	Piedmont			4	78	9.0	117	7.1	18.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1222312	HARRIS STEEL/BEAM SHIP	South Plainfield Boro	Piedmont			4	156	15.9	281	7.2	13.5	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022301	WHITEHOUSE SCHOOL	Readington Twp.	Piedmont			4	166	16.5	265	7.2	21.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1022370	MINALEX CORP	Readington Twp.	Piedmont			4	101	9.5	133	7.4	21.4	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106344	RT 31 PROFESSIONAL BLDG	Hopewell Twp.	Piedmont			4	196	74.2	156	6.9	36.9	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106383	MERRILL LYNCH	Hopewell Twp.	Piedmont			4	156	16.2	228	7.5	30.3	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)

Non-Community Water Systems

(*average data for aquifers in the region where system is located - values in parentheses correspond to 25th and 75th percentiles)

PWID	System Name	Municipality	Physiographic Province	Design Capacity (mgd)	System Size	Arsenic (ug/L)	Alkalinity (mg/L as)	Chloride (mg/L)	Hardness (mg/L as)	pH	Sulfate (mg/L)	Iron* (mg/L)	Manganese* (mg/L)	Nitrate* (mg/L)	Phosphate* (mg/L)	Silica* (mg/L)	TDS* (mg/L)
1810343	ALL DAY LEARNING CENTER	Hillsborough Twp.	Piedmont			4	148	13.5	372	7.0	182.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
2106321	VICTAULIC INC.	Franklin Twp.	Highlands			4						0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND-4.7)	0.01 (<0.01-0.02)	22 (19-29)	136 (105-185)
1410307	PARK MEADOWS INDUSTRIAL	East Hanover Twp.	Piedmont			4					756.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1008306	RAMBLING PINES DAY CAMP/	East Amwell Twp.	Piedmont			4						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND 5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1006341	ROUTE 31 ASSOCIATES	Clinton Twp.	Highlands			4						0.007 (0.004-0.018)	0.002 (ND-0.011)	0.76 (ND 4.7)	0.01 (<0.01-0.02)	22 (19-29)	135 (105-185)
0306503	KINDER CARE	Burlington Twp.	Inner Coastal Plain			4					22.2						
1091374	HUNTERDON MED CTR WELL #	Raritan Twp.	Piedmont			3.9					23.6	1	0.077	0.6 (ND 198)	0.06	9.1	136
1917301	LAKE NELSON SCHOOL	Piscataway Twp.	Piedmont			3.9	160	11.0	435	7.3	62.8	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021391	LIBERTY COURT CONDO ASSN	Raritan Twp.	Piedmont			3.8	168	158.0	340	7.5	370.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106377	PENNINGTON OFFICE PARK-H	Hopewell Twp.	Piedmont			3.8					15.7	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1021395	FLEMINGTON OUTLET CENTER	Raritan Twp.	Piedmont			3.7						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106317	IMBERLANE JUNIOR HIGH S	Hopewell Twp.	Piedmont			3.7		15.8	192	7.6	17.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1106316	BEAR TAVERN SCHOOL	Hopewell Twp.	Piedmont			3.7		36.4	176	7.9	20.0	0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
1107301	SIMONE INVESTMENT GROUP LLC.	Lawrence Twp.	Piedmont			3.6						0.016 (ND-0.26)	0.011 (ND-0.26)	1.6 (ND-5.5)	0.03 (0.03-0.1)	24 (19-34)	313 (217-478)
0112314	MIGRANT DAY CAMP	Hamilton Twp.	Inner Coastal Plain			3.5	0	3.5	6	5.3	5.0						
1413305	BASKING RIDGE WK CTR/ BELL ATI	Harding Twp.	Piedmont			3.3						1	0.077	0.6 (ND 198)	0.06	9.1	136

					median values	7.0	128.5	19.1	166.5	7.2	27.2
					average values	8.1	116.8	47.9	219.3	7.2	101.3

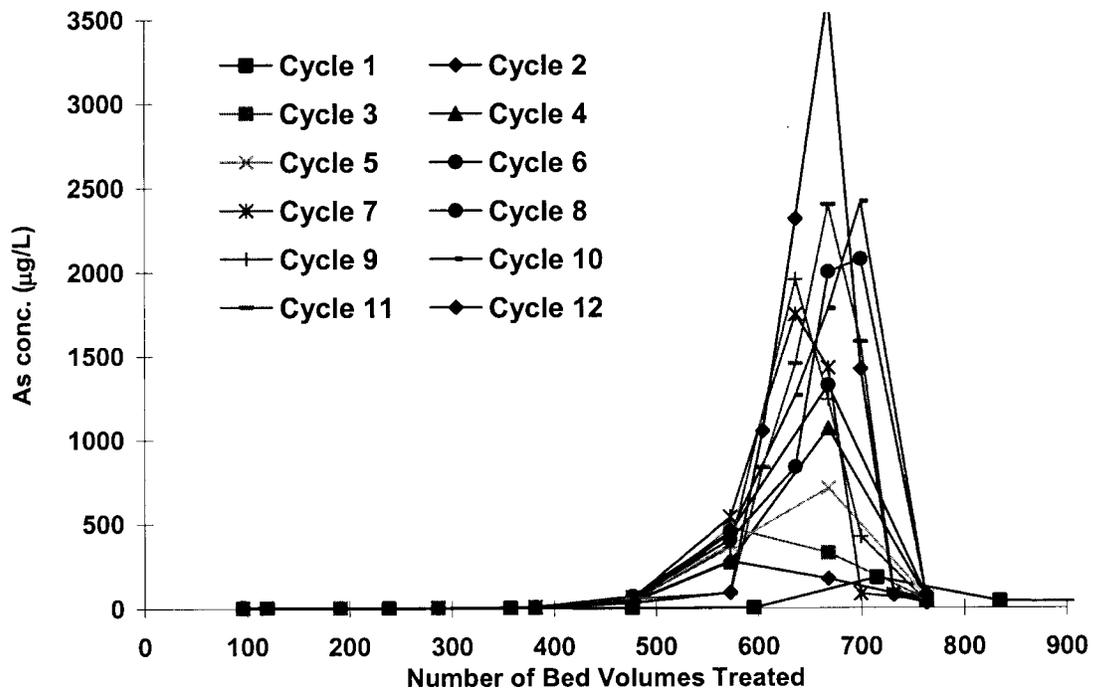|	
Valley and Ridge	1.4%
Highlands	8.8%
Piedmont	65.5%
Inner Coastal Plain	9.5%
Outer Coastal Plain	14.9%

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APPENDIX C

REPRESENTATIVE DATA ILLUSTRATING THE ARSENIC REMOVAL PERFORMANCE OF VARIOUS TREATMENT TECHNOLOGIES

Conventional ion exchange: pilot-scale (~20 gpm) – Tucson, AZ (Kwan et al.)
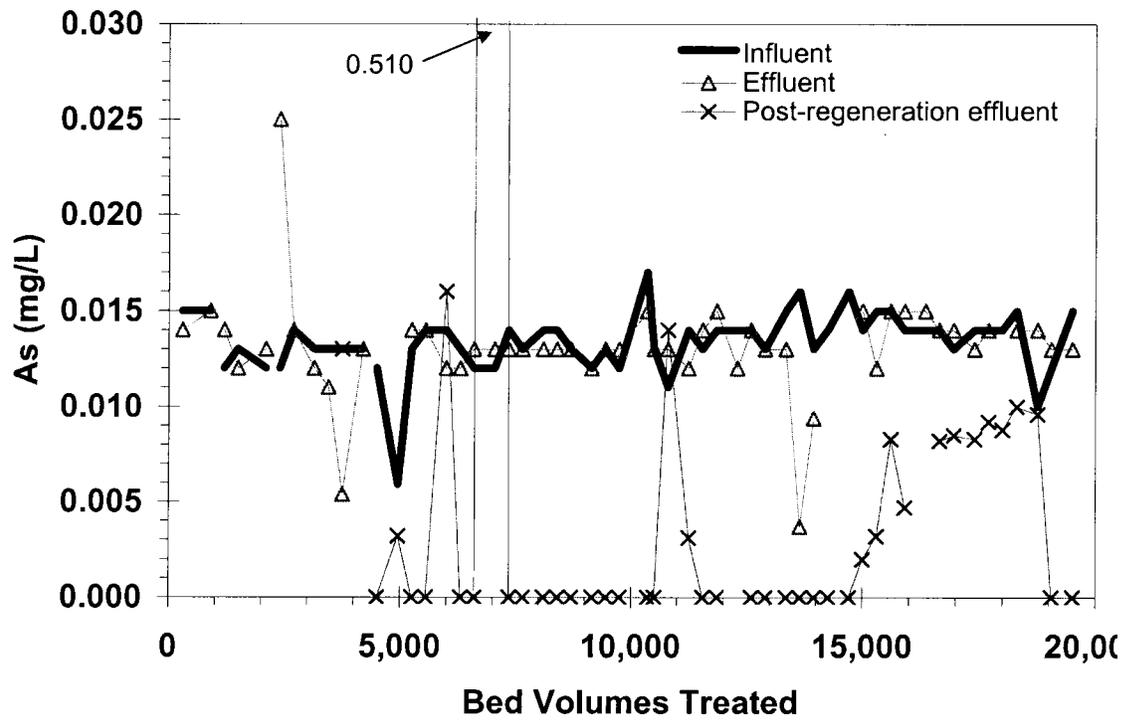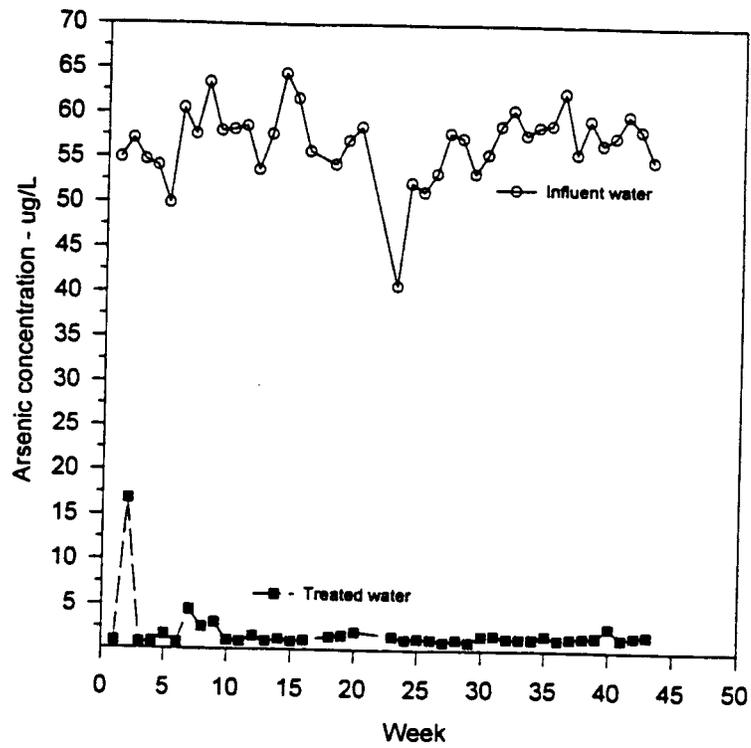

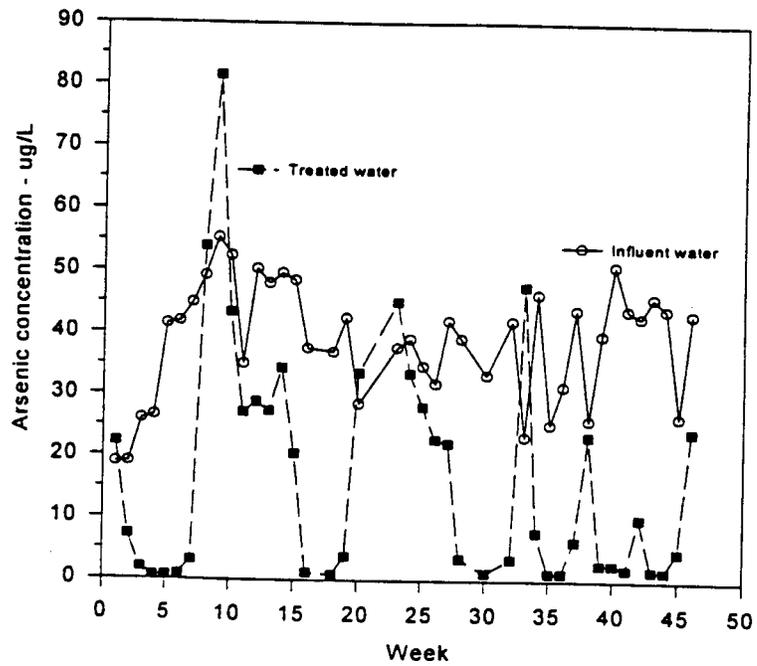**Conventional ion exchange: bench-scale (Chang)**

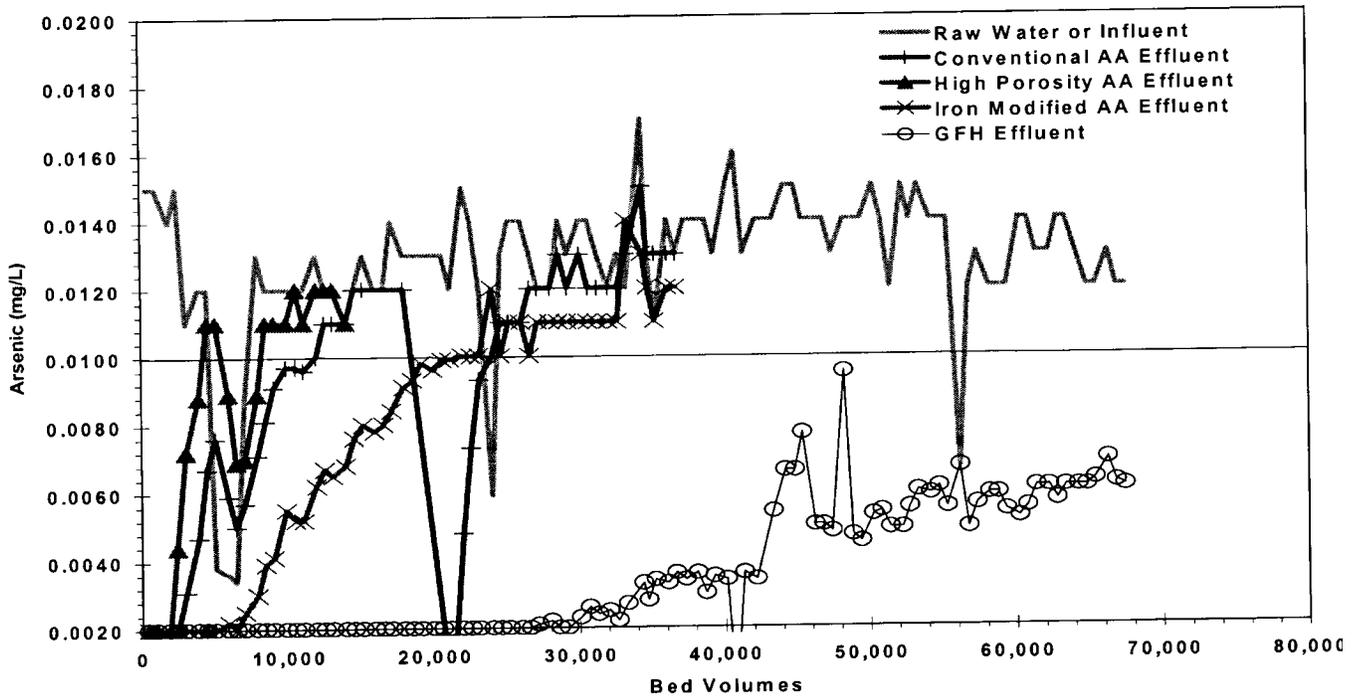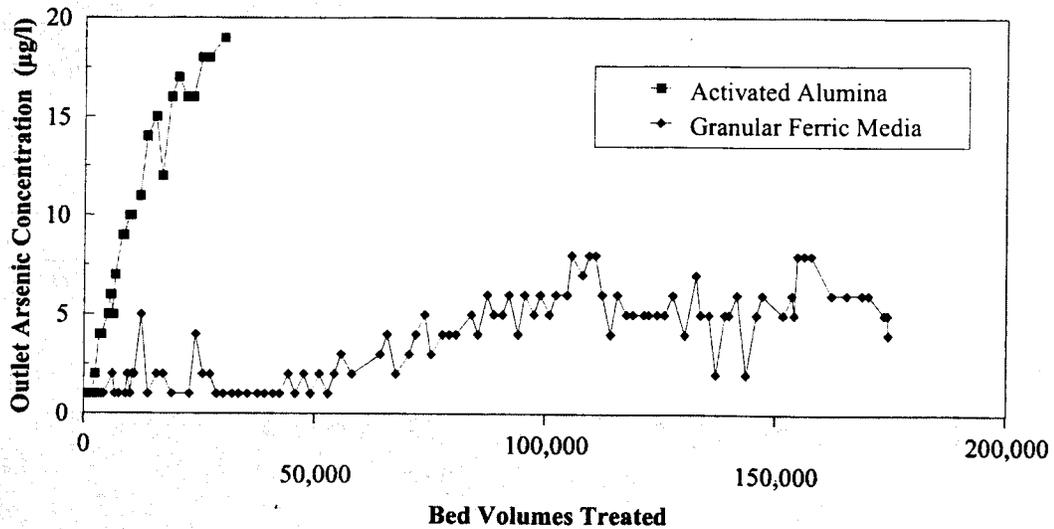**Conventional ion exchange: full-scale (NCWS) – New England area (Wang et al.)**

MMA Test Results

FJS Test Results

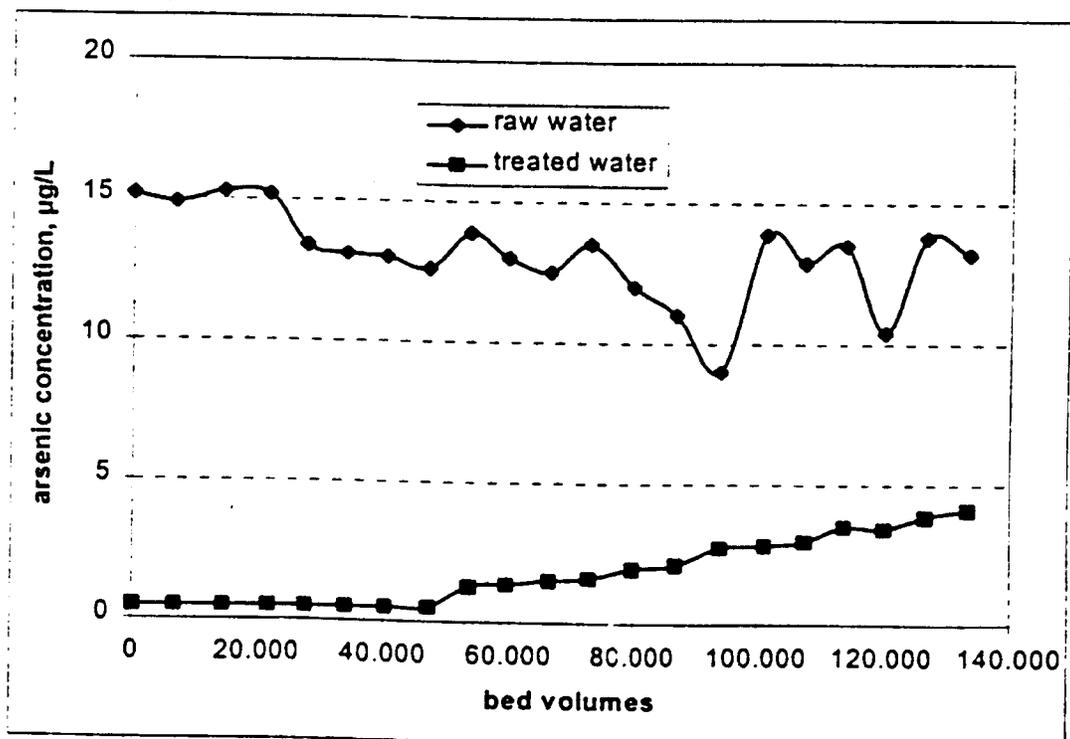**Granular ferric hydroxide/activated alumina: pilot-scale (~20 gpm) – Tucson, AZ (Galeziewski et al.)**

Granular ferric hydroxide/activated alumina: pilot-scale (~10 gpm) – Nottingham, England (Selvin et al.)
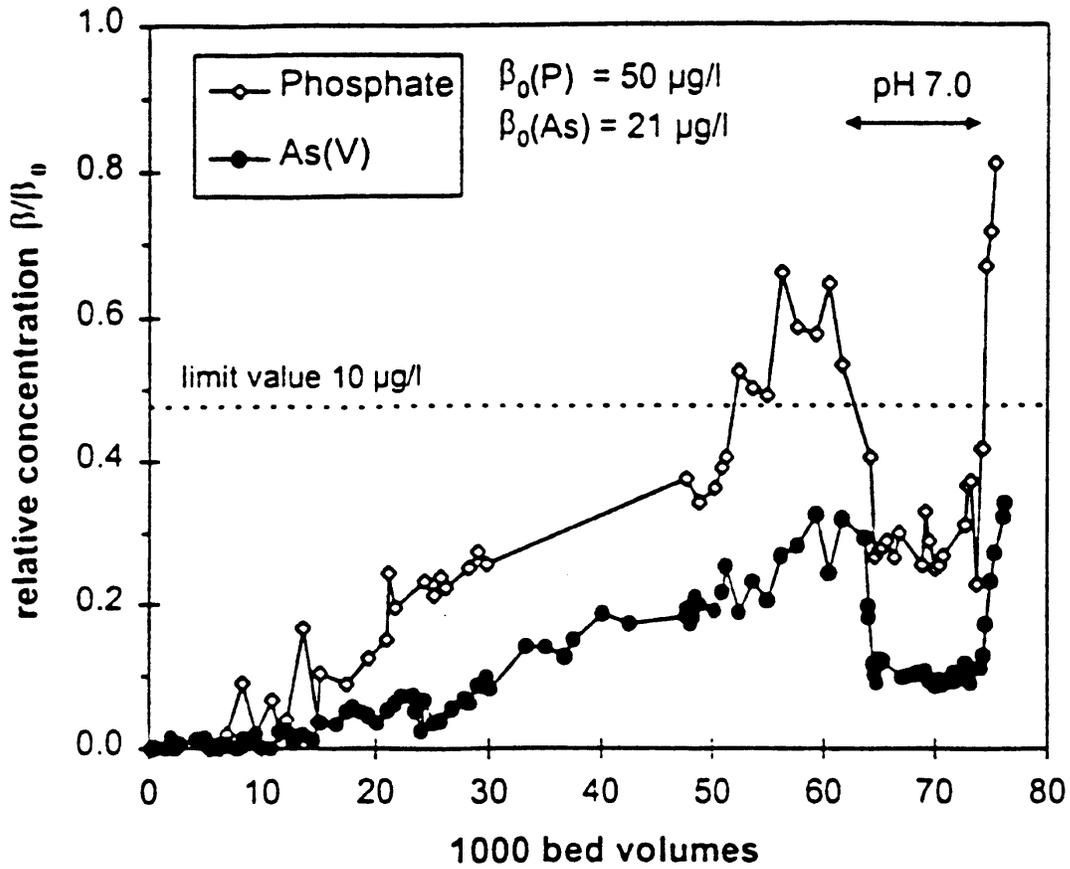
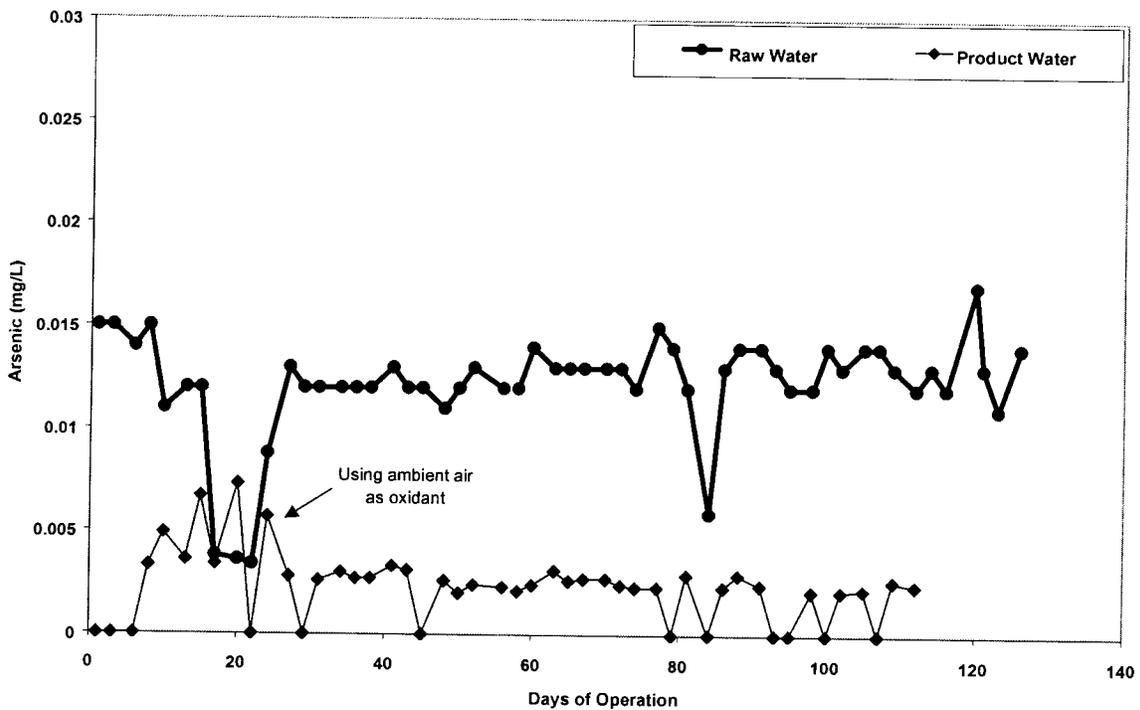**Granular ferric hydroxide: pilot scale system (~10 gpm) – Nottingham, England (Barnes et al.)**

Graph 1: Arsenic Removal using Granular Ferric Media
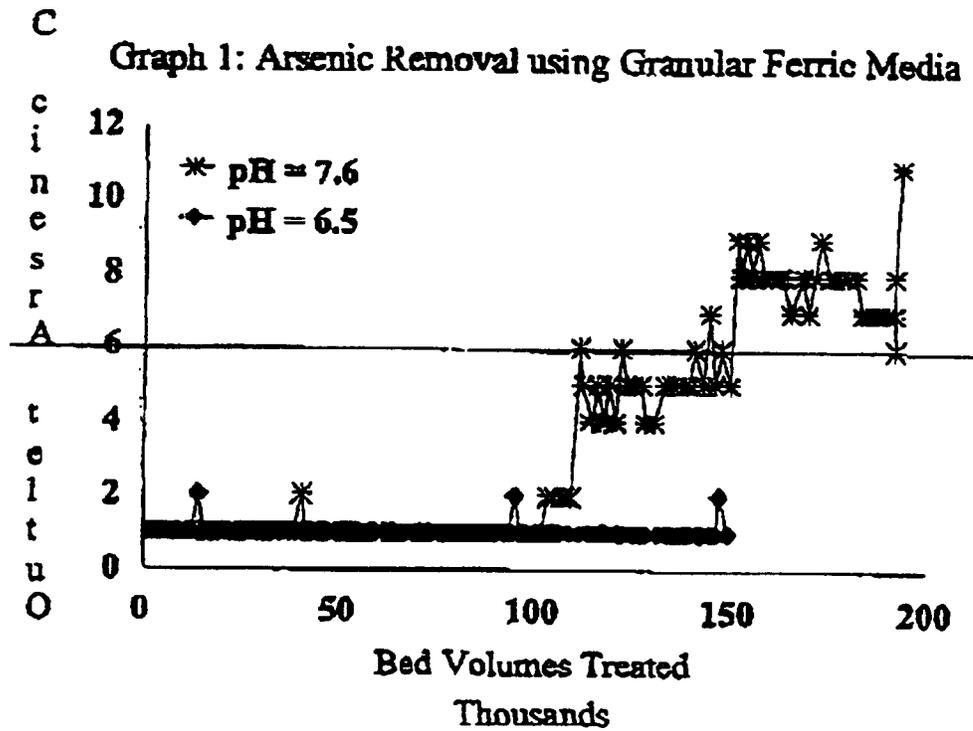
Granular ferric hydroxide: full-scale (0.1 MGD) – Wildeck, Germany (Driehaus)
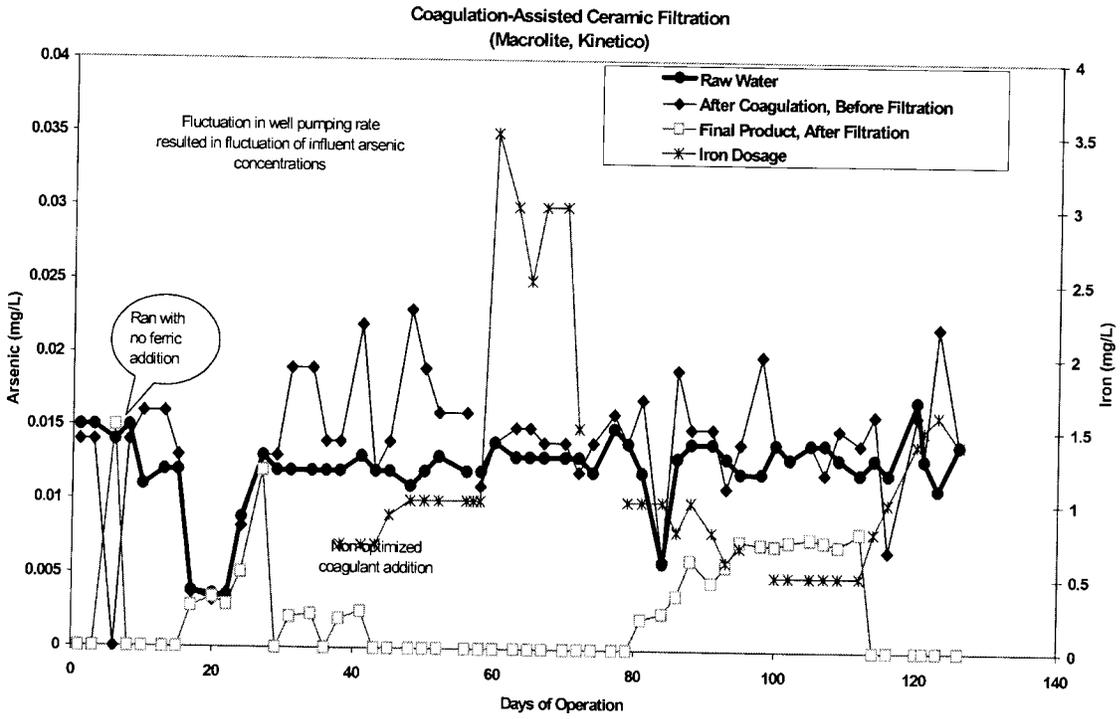
Granular ferric hydroxide: full-scale (0.3 MGD) – Stadtoldendorf, Germany (Jekel & Seith)

Microsand-assisted coagulation/settling: pilot-scale (~20 gpm) – Tucson, AZ (Chowdhury et al.)

Coagulation/media filtration: pilot-scale (~20 gpm) – Tucson, AZ (Kommineni et al.)

Coagulation-Assisted Ceramic Filtration
(Macrolite, Kinetico)

APPENDIX D

REFERENCES – ION EXCHANGE

APPENDIX E

REFERENCES – ACTIVATED ALUMINA
(see also Wang et al. in Appendix D)

APPENDIX F

REFERENCES – GRANULAR FERRIC HYDROXIDE
(see also Galeziewski et al. and Selvin et al. in Appendix E)

APPENDIX G

REFERENCES – COAGULATION/FILTRATION