An Assessment of the State of Nitrate Treatment Alternatives

FINAL REPORT

The American Water Works Association
Inorganic Contaminant Research and
Inorganic Water Quality Joint Project Committees

by
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June, 2011
Acknowledgements

Special thanks to the members of the AWWA Inorganic Contaminants Research and Inorganic Water Quality Project Subcommittee:

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Disclaimer

This document is intended as a guide of nitrate treatment technologies and should be used as an informational tool only. The contents of this document are solely the responsibility of the authors and do not necessarily represent the official views of supporting agencies. The selection and design of the most appropriate nitrate treatment alternative for a particular water system depends on a variety of factors and requires the expertise of experienced professional engineers. Discussion of proprietary technologies is intended to provide information about treatment alternatives and does not imply endorsement.
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Abbreviations

AFY  Acre Feet per Year
AWWA  American Water Works Association
BMP  Best Management Practice
BD  Biological Denitrification
CD  Chemical Denitrification
DBP  Disinfection By-Product
DL  Detection Limit
EBCT  Empty Bed Contact Time
ED  Electrodialysis
EDR  Electrodialysis Reversal
GAC  Granular Activated Carbon
GPM  Gallons per Minute
GWUDI  Groundwater Under Direct Influence (of Surface Water)
HERO™  High Efficiency Reverse Osmosis
HLR  Hydraulic Loading Rate
ISEP®  Ion Exchange Separation System
IX  Ion Exchange
LSI  Langelier Saturation Index
MBfR  Membrane Biofilm Reactor
MBR  Membrane Bioreactor
MCL  Maximum Contaminant Level
MGD  Million Gallons per Day
MIEX®  Magnetic Ion Exchange
NDMA  N-nitrosodimethylamine
O&M  Operations and Maintenance
POE  Point-of-Entry
POU  Point-of-Use
RO  Reverse Osmosis
SBA IX  Strong Base Anion Exchange
SBR  Sequencing Batch Reactor
SDWA  Safe Drinking Water Act
SED  Selective Electrodialysis
SMI  Sulfur Modified Iron
TDS  Total Dissolved Solids
TSS  Total Suspended Solids
ULPRO  Ultra-Low Pressure Reverse Osmosis
USBR  Upflow Sludge Blanket Reactor
VSEP  Vibratory Shear Enhanced Process
WAC  Weak Acid Cation Exchange
WBA IX  Weak Base Anion Exchange
ZVI  Zero Valant Iron

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0.0 Executive Summary

0.1 Objective

Jacobs Engineering Group, Inc. (Jacobs), in collaboration with the University of California at Davis (UC Davis), has conducted An Assessment of the State of Nitrate Treatment Alternatives for the American Water Works Association (AWWA) Inorganic Contaminant Research and Inorganic Water Quality Joint Project Committees. The purpose of this document is to provide a detailed guide to the current state of nitrate treatment alternatives that can be used as a reference tool for the drinking water community.

0.2 Background

Nitrate contamination of potable water sources is becoming one of the most important water quality concerns in the United States. The maximum contaminant level (MCL) for nitrate is 10 mg/L as nitrogen (N). The major health concern of nitrate exposure through drinking water is the risk of methemoglobinemia, or “blue baby syndrome,” especially in infants and pregnant women. Due to the nature of the infant digestive system, nitrate is reduced to nitrite which can render hemoglobin unable to carry oxygen (SWRCB, 2010). Nitrate is naturally occurring at low levels in most waters, but it is particularly prevalent in groundwater that has been impacted by certain agricultural, commercial or industrial activities. Of specific concern are crop fertilization activities and discharges from animal operations, wastewater treatment facilities, and septic systems. Small rural communities are particularly impacted by nitrate (Pacific Institute, 2011). Nitrate presents unique water treatment challenges. The United States Environmental Protection Agency (USEPA) lists only anion exchange (IX), reverse osmosis (RO), and electrodialysis reversal (EDR) as accepted potable water treatment methods for nitrate removal (USEPA, 2010). Due to the production of high-strength brine residuals, sustainable application of these three technologies is often limited by a lack of local residual disposal options and the challenge of increasing salt loads. The lack of affordable and feasible nitrate treatment alternatives can force impacted utilities to remove nitrate-contaminated sources from their available water supply. In many instances, this action can severely compromise a water utility’s ability to provide an adequate supply of safe and affordable potable water.
The need for additional nitrate treatment technologies has driven the drinking water community to begin developing alternative options to effectively remove nitrate while limiting cost and brine production challenges. Promising treatment options include weak base anion (WBA) exchange and improvements in strong base anion (SBA) exchange such as low brine residual technologies; biological treatment using fluidized bed, fixed bed, and membrane biofilm (MBfR) reactors; and chemical reduction using media such as zero valent iron (ZVI) and sulfur modified iron (SMI). A summary of the options to address nitrate contamination of drinking water is presented in Figure ES.1. In this diagram treatment options are classified in terms of their ability to either remove nitrate to a residual waste stream or transform nitrate to other nitrogen species through reduction.

**Figure ES-1  Summary of Nitrate Management Options.**

```
Non-Treatment Options

Well Abandonment  Wellhead Protection and Land Use Management  Alternative Sources and Source Modification  Blending

Treatment Options

Nitrate Removal  Hybrid Systems  Nitrate Reduction

Nitrate Removal

Ion Exchange  Reverse Osmosis  Electrodialysis

Conventional, Specialized Resin, Counter Current, Multiple Vessel Configuration, WBA IX  Process & Membrane Improvement and Modification  EDR SED

Nitrate Reduction

Biological Denitrification  Chemical Denitrification

Biological Denitrification

Fixed Bed Fluidized Bed MBR/MBfR  ZVI SMI Other Media
```

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0.3 Approach

This report includes a comprehensive literature review and case studies of specific systems across the range of nitrate treatment alternatives. The literature review is intended to provide background information about current and emerging potable water treatment alternatives to address nitrate contamination. In addition to peer-reviewed literature, information found in the “grey papers” of conference proceedings has been included to assure capture of the most recent technology developments. For each of the major treatment technologies, subsections of the literature review detail the following:

- Design considerations including water quality, system layout and site considerations; residuals management and disposal; and maintenance, monitoring and operational complexity,
- Cost considerations,
- Selected research, and
- A summary of advantages and disadvantages.

Information is summarized in tables whenever appropriate, including a summary table of selected research studies for each of the major treatment technologies (Appendix).

A survey was conducted to collect detailed information about the application of nitrate treatment. A subset of utilities, currently treating for nitrate and/or in design for future treatment, was included in the survey. The survey was developed to gather information with respect to the benefits and limitations of the various nitrate treatment technologies and was conducted via phone and in-person when applicable. The list of utilities included in the survey was developed with the intention of covering a range of utilities with respect to geographic location, treatment type, population size and residual handling techniques (Table ES.1).

Detailed case studies have been compiled for each of the treatment technologies where full-scale facilities have been in operation or are moving ahead with design.
Table ES-1  Utilities Included in the Case Studies.

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<th>Treatment Type</th>
<th>Location</th>
<th>Capacity (gpm)</th>
<th>Avg. Influent Nitrate (mg/L as N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Ion Exchange</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Conventional ion exchange with blending</td>
<td>California</td>
<td>400</td>
<td>7-12</td>
</tr>
<tr>
<td>2</td>
<td>Conventional ion exchange with blending</td>
<td>California</td>
<td>400</td>
<td>~10</td>
</tr>
<tr>
<td>3</td>
<td>Counter Current Ion Exchange (MIEX®)</td>
<td>Indian Hills, CO</td>
<td>50</td>
<td>12-16</td>
</tr>
<tr>
<td>4</td>
<td>Multiple vessel ion exchange</td>
<td>California</td>
<td>500-900</td>
<td>8-20</td>
</tr>
<tr>
<td>5</td>
<td>Multiple vessel ion exchange</td>
<td>Chino, CA</td>
<td>5000</td>
<td>9-45</td>
</tr>
<tr>
<td></td>
<td><strong>Reverse Osmosis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Reverse osmosis and blending</td>
<td>Bakersfield, CA</td>
<td>120</td>
<td>17-19</td>
</tr>
<tr>
<td>7</td>
<td>Reverse osmosis, exploring biological reduction</td>
<td>Brighton, CO</td>
<td>4600</td>
<td>11-20</td>
</tr>
<tr>
<td>8</td>
<td>Reverse osmosis and blending</td>
<td>Arlington Desalter, Riverside, CA</td>
<td>4583</td>
<td>10-20</td>
</tr>
<tr>
<td></td>
<td><strong>Combined Reverse Osmosis and Ion Exchange</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Reverse osmosis, ion exchange and blending</td>
<td>Chino Desalter I, Chino, CA</td>
<td>4940 (RO), 3400 (IX)</td>
<td>32-65</td>
</tr>
<tr>
<td>10</td>
<td>Reverse osmosis, ion exchange and blending</td>
<td>Chino Desalter II, Mira Loma, CA</td>
<td>4167 (RO), 2778 (IX)</td>
<td>15-48</td>
</tr>
<tr>
<td></td>
<td><strong>Electrodialysis (ED/EDR/SED)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Electrodialysis Reversal (EDR)</td>
<td>Spain</td>
<td>3,260 (each, 2 systems)</td>
<td>~18</td>
</tr>
<tr>
<td>12</td>
<td>Selective Electrodialysis (SED)</td>
<td>Israel</td>
<td>310</td>
<td>19-20</td>
</tr>
<tr>
<td></td>
<td><strong>Biological Denitrification</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Implementing fluidized bed biological reduction</td>
<td>Rialto, CA</td>
<td>2000-4000</td>
<td>17-19</td>
</tr>
<tr>
<td>14</td>
<td>Implementing fixed bed biological reduction</td>
<td>Riverside, CA</td>
<td>1670</td>
<td>10-20</td>
</tr>
</tbody>
</table>
0.4 Summary of Findings

0.4.1 Non-Treatment Options
The focus of this assessment is the current state of nitrate treatment alternatives. However, in practice, non-treatment options are generally considered first as they can often be more sustainable and less costly. Non-treatment options include wellhead protection, land use management, well inactivation, source modification, development of alternative sources (including consolidation/connection to a nearby system), and blending. Blending was found to be the most common method to address nitrate contamination. When a low nitrate concentration water supply source is available, dilution of high nitrate concentration sources to produce water with nitrate concentrations below the MCL is typically more cost effective than installing treatment.

0.4.2 Treatment Options
Nitrate treatment technologies were categorized into five major types. Ion exchange (IX), reverse osmosis (RO), and electrodialysis/electrodialysis reversal (ED/EDR) remove nitrate to a concentrated waste stream, while biological denitrification (BD) and chemical denitrification (CD) transform nitrate to other nitrogen species through reduction. Common concerns in the application of the removal technologies include waste management costs and treatment interference from other water quality parameters (e.g., hardness and sulfate). Pretreatment is often required to avoid fouling or scaling of the resin for IX and the membranes for RO and ED/EDR. Due to the destruction of nitrate, both biological and chemical denitrification have the potential for more sustainable treatment without brine residuals but also have limitations to consider. Full scale application of these nitrate treatment options is currently limited.

The selection of the most appropriate treatment option depends on various key factors specific to the needs and priorities of individual water systems. A brief comparison of fundamental design considerations, advantages and disadvantages of these treatment options is listed in Table ES.2. It is important to note that the contents of Table ES.2 are not intended to provide a comprehensive set of criteria for treatment options. Other important criteria in determining the best treatment option, which are site specific and cannot be broadly generalized, include capital and operations and maintenance (O&M) costs, system size (capacity), and system
footprint. Overall, there is no single treatment option that can be considered the best method for nitrate removal across all water quality characteristics and for all systems.
<table>
<thead>
<tr>
<th>Full Scale Systems</th>
<th>Ion Exchange</th>
<th>Reverse Osmosis</th>
<th>Electrodialysis</th>
<th>Biological Denitrification</th>
<th>Chemical Denitrification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Type</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Common Water Quality Design Considerations</td>
<td>Sulfate, iron, manganese, total suspended solids (TSS), metals (e.g., arsenic), hardness, organic matter</td>
<td>Turbidity, iron, manganese, SDI, particle size, TSS, hardness, organic matter, metals (e.g., arsenic)</td>
<td>Turbidity, iron, manganese, TSS, hydrogen sulfide, hardness, metals (e.g., arsenic)</td>
<td>Temperature and pH, anoxic conditions</td>
<td>Temperature and pH</td>
</tr>
<tr>
<td>Pretreatment Needs</td>
<td>Pre-filter, address hardness</td>
<td>Pre-filter, address hardness</td>
<td>Pre-filter, address hardness</td>
<td>pH adjustment, nutrient and substrate addition, need for anoxic conditions</td>
<td>pH adjustment</td>
</tr>
<tr>
<td>Post-treatment Needs</td>
<td>pH adjustment</td>
<td>pH adjustment Remineralization</td>
<td>pH adjustment Remineralization</td>
<td>Filtration, disinfection, possible substrate adsorption</td>
<td>pH adjustment, iron removal, potential ammonia control</td>
</tr>
<tr>
<td>Waste/Residuals Management</td>
<td>Waste brine</td>
<td>Concentrate</td>
<td>Concentrate</td>
<td>Sludge/biosolids</td>
<td>Sludge/biosolids</td>
</tr>
<tr>
<td>Start-up Time</td>
<td>Minutes</td>
<td>Minutes</td>
<td>Minutes</td>
<td>Initial plant startup: Days to weeks After reaching steady state: Minutes</td>
<td>Minutes</td>
</tr>
<tr>
<td>Water Recovery</td>
<td>Conventional (97%) Low brine (Up to 99.9%)</td>
<td>Up to 85%</td>
<td>Up to 95%</td>
<td>Nearly 100%</td>
<td>Not demonstrated full scale</td>
</tr>
<tr>
<td>Advantages</td>
<td>Nitrate selective resins, common application, multiple contaminant removal</td>
<td>Multiple contaminant removal, desalination (TDS removal)</td>
<td>Multiple contaminant removal, higher water recovery (less waste), desalination, unaffected by silica</td>
<td>No waste brine or concentrate, nitrate reduction rather than transfer to a waste stream, high water recovery, and potential for multiple contaminant removal</td>
<td>No waste brine or concentrate, nitrate reduction rather than transfer to a waste stream, and potential for multiple contaminant removal</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Potential for nitrate peaking, high chemical use (salt), brine waste disposal, potential for disinfection byproduct (DBP) formation (e.g., NDMA)</td>
<td>Membrane fouling and scaling, lower water recovery, operational complexity, energy demands, waste disposal</td>
<td>Energy demands, operational complexity, waste disposal</td>
<td>Substrate addition, potentially more complex, high monitoring needs, possible sensitivity to environmental conditions, risk of nitrite formation (potential incomplete denitrification), post-treatment to address turbidity standards and 4-log virus removal (state dependent)</td>
<td>Inconsistency of nitrate reduction, risk of nitrite formation (potential incomplete denitrification), reduction to ammonia, lack of full scale systems, pH and temperature dependence, possible need for iron removal</td>
</tr>
</tbody>
</table>
0.4.2.1 Ion Exchange (IX)

The most commonly used nitrate treatment method is IX. Anion exchange for nitrate removal is similar to a water softener, with nitrate ions removed rather than hardness ions. Nitrate is removed from the treatment stream by displacing chloride on an anion exchange resin. Subsequently, regeneration of the resin is necessary to remove the nitrate from the resin. Regeneration is accomplished by using a highly concentrated salt solution resulting in the displacement of nitrate by chloride. The result is a concentrated waste brine solution high in nitrate that requires disposal. The most significant drawback of this treatment option is the cost for disposal of waste brine, especially for inland communities. The volume of the brine is largely dependent on the raw water quality and the configuration of the system.

Key factors in the consideration of IX include the pretreatment requirements to avoid resin fouling, the potential need for nitrate selective resin, the frequency of resin replacement, the possible post-treatment requirements to address corrosion or other product water quality concerns (e.g., the potential for NDMA formation), and the management of waste brine. If waste brine disposal options are not limiting, IX can be the best option for low to moderate nitrate contamination and removal of multiple contaminants (including arsenic, perchlorate and chromium). Application of IX may not be feasible for extremely high nitrate levels due to salt use and waste volume. Current research on brine treatment alternatives may lead to the development of technologies capable of effectively addressing the disposal concern; however, the costs for full scale implementation of this are unknown at this point.

Modifications to conventional IX have emerged in recent years offering low brine alternatives with improved efficiency. It is important to note that the efficiency of IX systems is dependent on the raw water characteristics and there can be cases where conventional IX systems yield greater water efficiency than a modified system that is implemented at a location with lesser water quality.

Another promising alternative to consider for the future is weak base ion exchange (WBA IX). This emerging technology is more operationally complex than conventional IX, but may offer the advantage of waste recycling as fertilizer.
0.4.2.2 Reverse Osmosis (RO)

As the second most common nitrate treatment alternative, RO can be feasible for both municipal and Point-of-Use applications and can be used simultaneously for desalination and removal of nitrate and many co-contaminants. Following pretreatment to prevent membrane fouling and scaling, water is forced through a semi-permeable membrane under pressure such that the water passes through, while contaminants are impeded by the membrane.

Key factors in the consideration of RO are the pretreatment requirements, the trade-off between water recovery and power consumption, the management of waste concentrate, and the typically higher costs relative to IX. One deciding factor favoring the selection of RO over IX for nitrate removal would be the need to address salinity.

Recent advancements in membrane technology and optimization of pre- and post-treatment have led to increases in the efficiency of RO treatment systems. For example, the use of Ultra-Low Pressure Reverse Osmosis (ULPRO) membranes enables lower power consumption.

0.4.2.3 Electrodialysis (ED, EDR, SED)

The use of ED in potable water treatment has increased in recent years, offering the potential for lower residual volumes through improved water recovery, the ability to selectively remove nitrate ions, and the minimization of chemical and energy requirements. ED works by passing an electric current thru a series of anion and cation exchange membranes that trap nitrate and other ions in a concentrated waste stream. To minimize fouling and thus the need for chemical addition, the polarity of the system can be reversed with electrodialysis reversal (EDR). By reversing the polarity (and the solution flow direction) several times per hour, ions move in the opposite direction through the membranes, minimizing buildup.

Key factors in the consideration of EDR are the pretreatment requirements, the operational complexity of the system, the limited number of system manufacturers, the lack of full-scale installations for nitrate removal from potable water in the United States, and the management of waste concentrate. Like RO, EDR is commonly used for desalination and can be an alternative for nitrate treatment of high TDS waters. In contrast to conventional RO, EDR is unaffected by silica. EDR costs are similar to RO and evidence suggests that EDR can be the preferable option as the Silt Density Index (SDI) increases. For very small particle sizes, robust pretreatment can be necessary for RO. It is important to note that the EDR process does not directly filter the
treatment stream through the membranes; contaminants are transferred out of the treatment stream and trapped by the membranes. This generally minimizes membrane fouling, decreasing pretreatment requirements in comparison to RO.

0.4.2.4 Biological Denitrification (BD)

Biological denitrification in potable water treatment is more common in Europe with recent full-scale systems in France, Germany, Austria, Poland, Italy and Great Britain. To date, full-scale drinking water applications in the United States are limited to a single plant in Coyle, OK (no longer online). However, two full-scale systems are anticipated in California in the next couple of years. Biological denitrification relies on bacteria to transform nitrate to nitrogen gas (through reduction). Substrate and nutrient addition is necessary and post-treatment can be more intensive than for the removal processes. Biological denitrification offers the ability to address multiple contaminants and the avoidance of costly waste brine disposal.

Key factors in the consideration of biological denitrification are the chemical requirements, the need for anoxic conditions, the level of operator training, the robustness of the system, and the post-treatment requirements. State regulations are expected to vary and, until more experience with the application of biological denitrification for potable water treatment is obtained in the United States, pilot and demonstration requirements may be intensive. Typically biological treatment is thought to have a larger footprint; however, with the latest design configurations, the system footprint may be comparable to that of RO or EDR systems.

With reduction of nitrate to nitrogen gas, the lack of a problematic brine waste stream is a clear advantage of biological treatment over the removal processes. Biological treatment has the potential to provide a sustainable nitrate treatment option for the long term. More will be known with the completion of the anticipated full-scale systems in California, cost estimation suggests that biological treatment can be economically competitive with IX.

0.4.2.5 Chemical Denitrification (CD)

Chemical denitrification uses metals to transform nitrate to other nitrogen species. As an emerging technology, no full-scale chemical denitrification systems have been installed in the United States for nitrate treatment of potable water and application for nitrate treatment has been strictly limited to bench and pilot scale studies. A significant body of research has explored the use of zero valent iron (ZVI) in denitrification. Several patented granular media options have
also been developed including sulfur modified iron (SMI) media, granular clay media and powdered metal media.

Key factors in the consideration of chemical denitrification are the reliability and consistency of nitrate reduction, the lack of full-scale installations, the type of media, and the dependence on temperature and pH. Chemical denitrification has the potential to become a feasible full-scale nitrate treatment alternative, with the advantage of reducing nitrate to other nitrogen species and avoiding the need to dispose of a concentrated waste stream. However, currently this option is an emerging technology in need of additional pilot- and full-scale testing. Due to the potential benefits, further research and optimization of chemical denitrification systems will likely make this a competitive option in the future, especially for multiple contaminants (e.g., arsenic and chromium).

0.5 Summary and Conclusions

- Current full-scale nitrate treatment installations in the United States consist predominantly of IX and RO. While EDR is a feasible option for nitrate removal from potable water, the application of EDR is generally limited to waters that have high TDS or silica. The use of biological denitrification to address nitrate contamination of drinking water is more common in Europe than in the U.S.. However, this option is emerging in the U.S. and two full-scale systems are expected in a few years. Chemical denitrification may become a feasible nitrate treatment option in the future; however, the lack of current full-scale implementation suggests the need for further research, development and testing.

- Brine reuse and treatment are vital to the continued reliance on IX for nitrate treatment of potable water. The low brine technologies offer a minimal waste approach and current research and development of brine treatment alternatives seem to be lighting the path toward future progress.

- In regions with declining water quality and insufficient water quantity, the need to address multiple contaminants will increase in the future, suggesting the future dominance of technologies capable of multiple contaminant removal. In this context, for any individual water source or system, the most appropriate technology will vary with the contaminants requiring mitigation. Although complex, analysis of the optimal treatment
option for pairs and groups of contaminants will assist in the treatment design and selection. In such scenarios, the best treatment option for nitrate may not be the most viable overall.

- Currently and into the future, selection of the optimal and most cost effective potable water treatment options will depend not only on the specific water quality of a given water source, but also on the priorities of a given water system. If land is limited, the typical configuration required for biological treatment may not be feasible. If brine waste disposal options are costly or limited, implementation of denitrification treatment or development of brine recycling and treatment may be the most suitable option.

- When deciding on nitrate treatment, the characteristics of the water system must be taken into account as well. With consideration of economies of scale, many rural small water systems cannot afford to install treatment. Even with financial assistance to cover capital costs, the long term viability of a treatment system can be undermined by O&M costs that are simply not sustainable. For such systems, treatment can become more affordable through consolidation of multiple small water systems into larger combined water systems that can afford treatment as a conglomerate. With a continued decline in water quality, non-treatment options alone, like blending or drilling a new well, may become insufficient measures for a water system to provide an adequate supply of safe and affordable potable water. Especially in rural small communities, perhaps the most promising approach will be a combination of consolidation and treatment.

- While current cost considerations are commonly the driving force in selecting nitrate treatment, it is essential to consider the long term implications of current industry decisions. For example, it may be cost effective for a particular system to utilize conventional IX currently, but future water quality changes (e.g., increasing nitrate levels, co-contamination, high salt loading), discharge regulations, or disposal fees may lead to an unmanageable increase in costs. Environmental sustainability in drinking water treatment is being addressed with brine treatment alternatives and denitrification options. It is important to approach the future of drinking water treatment with the mindset that environmental sustainability and economic sustainability are tightly interwoven.
• Within the drinking water community, the options typically considered to address nitrate contamination are IX and RO. Alternative technologies are available because, under some circumstances, they offer advantages over IX and RO. New technologies will continue to be investigated and developed because no single option is ideal for all situations. There is not a nitrate treatment option currently available that can affordably address all possible scenarios. The following diagram is a rough guide for treatment technology selection based on water quality concerns and possible priorities for a given water source or system (Table ES.3). This diagram includes generalizations and is not intended to be definitive. In the selection of nitrate treatment technologies the unique needs of an individual water system must be assessed by professional engineers to optimize treatment selection and design.

Table ES-3  Comparison of Major Treatment Types\(^1\).

<table>
<thead>
<tr>
<th>Concerns</th>
<th>IX</th>
<th>RO</th>
<th>EDR</th>
<th>BD</th>
<th>CD</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Nitrate Removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High TDS Removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenic Removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radium and Uranium Removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium Removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perchlorate Removal</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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</table>

<table>
<thead>
<tr>
<th>Priorities</th>
<th>IX</th>
<th>RO</th>
<th>EDR</th>
<th>BD</th>
<th>CD</th>
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<tr>
<td>High Hardness Not a Major Concern</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Training/ Ease of operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimize Capital Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimize Ongoing O&amp;M Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimize Footprint</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry Experience</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Ease of Waste Management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Ion Exchange (IX), Reverse Osmosis (RO), Electrodialysis Reversal (EDR), Biological Denitrification (BD), Chemical Denitrification (CD). This table offers a generalized comparison and is not intended to be definitive. There are notable exceptions to the above classifications.
1.0 Introduction

Nitrate contamination of potable water sources is becoming one of the most important water quality concerns in the United States. The federal maximum contaminant level (MCL), 10 mg/L nitrate as nitrogen (N), is currently being approached or exceeded in potable water supply sources at locations throughout the United States (Nolan et al., 2002; USEPA, N.D.; and Chen et al., 2009). A major source of nitrate contamination is fertilizer. Application of fertilizer in excess of the amount taken up by crops leads to leaching into the groundwater. Leakage from livestock feedlots and waste storage also contributes to the nitrate problem (LLNL, 2002). Additional sources include wastewater treatment discharge, faulty septic systems and various industrial applications. Due to the typical sources, nitrate contamination is more common in rural agricultural areas. The major health concern of nitrate exposure through drinking water is the risk of methemoglobinemia, especially in infants and pregnant women. Due to the nature of the infant digestive system, nitrate is reduced to nitrite which can render hemoglobin unable to carry oxygen (SWRCB, 2010).

1.1 Management Options for Nitrate in Potable Water

To meet the nitrate MCL in the provision of potable water, both non-treatment and treatment options are considered. Source management with non-treatment can sometimes provide less costly solutions through wellhead protection, land use management, well abandonment, source modification, development of alternative sources (including consolidation or connection to a nearby system), or blending. The feasibility of non-treatment options can be limited by various factors including location, budget, source availability, and variability of water quality (i.e., fluctuations in nitrate levels), resulting in the need for treatment to remove or reduce nitrate.

Current treatment methods include ion exchange (IX), reverse osmosis (RO), electrodialysis/electrodialysis reversal (ED/EDR), biological denitrification (BD) and chemical denitrification (CD). These nitrate management options are examined in detail to assess research findings, capital and O&M costs, typical limitations and the latest improvements. Design and cost considerations will be addressed with the development of guidelines for determining the most appropriate treatment option based on source water quality and other
water system characteristics. The inclusion of Point-of-Entry (POE) and Point-of-Use (POU) treatment is also essential to a comprehensive examination of nitrate treatment. The Safe Drinking Water Act (SDWA) [Section 1412(b)(4)(E)(ii)] (USEPA, 1998) identifies both POE and POU treatment units as options for compliance technologies for small systems (although state regulations governing the use of POU and POE devices for water system compliance may be restrictive). Lastly, hybrid systems are explored. The combination of multiple treatment technologies, including several developing brine treatment alternatives, can maximize the advantages of each option. The goal of this investigation is to provide an overview of management strategies and treatment options, highlighting the most recent advances and elucidating costs and common problems in application.
2.0 Non-Treatment Options for Nitrate Contaminated Potable Water

2.1 Well Abandonment

With adequate capacity from other sources, the simplest option for management of nitrate contaminated potable water sources is well abandonment. However, the lack of sufficient alternative water supplies often rules out well abandonment as an option. Based on a recent survey conducted by the American Water Works Association (AWWA), 30.4% (17/56) of survey participants with wells impacted by nitrate selected well abandonment as the implemented option for addressing nitrate contamination (Weir & Roberson, 2010, Weir and Roberson, 2011). It is important to determine the local requirements for safely removing a well from service. For proper abandonment, local requirements can include covering, sealing and plugging of the well to prevent contamination and to avoid hazardous conditions. Inactivation or abandonment of a well differs from well destruction. Through inactivation or temporary abandonment, the well can be brought back online in the future (e.g., when treatment is installed). In contrast, well destruction involves the filling of a well, making it no longer viable.

2.2 Wellhead Protection and Land Use Management

While limiting current nitrate contamination of groundwater will not immediately remove the need for treatment, over time, load reduction will minimize source water nitrate levels. Agricultural practices, management of dairies, control of wastewater treatment plant discharge, and monitoring and remediation of septic tanks can be improved to minimize nitrogen loading. For example, a project addressing well head protection and land use management performed by the University of Waterloo (Rudolph, 2010) successfully decreased groundwater nitrate levels within a two year travel time from 17 to 7 mg/L total stored nitrogen. Reduced nitrogen loading was accomplished by purchasing agricultural land and implementing Best Management Practices (BMPs).
2.3 Development of Alternative Sources and Source Modification

With adequate information about the nitrate distribution and movement in the subsurface, a new well can potentially be developed to access higher quality source water. Due to the anthropogenic nature of the contamination, nitrate concentration typically decreases with depth (WA DOH, 2005). If suitable water quality exists, drilling a deeper well can remove the need for nitrate treatment. However, the quality improvements must be balanced by a potential decrease in source capacity. Due to drilling and pumping requirements, capital and operational costs increase with the depth to uncontaminated water. When considering the installation of a deeper well to avoid nitrate contamination, it is important to be aware of the risk of encountering other water quality concerns at greater depths (e.g., arsenic).

Connecting to a nearby water system that is not impacted by nitrate or to a larger system that can afford nitrate treatment is often the best option for smaller systems. For example, since 1995, the City of Modesto, CA has been in charge of providing compliant water to the residents of Grayson; an ion exchange plant is used for nitrate removal (Scott, 2010). Similarly, consolidation of multiple small systems can decrease the cost of treatment per customer to more reasonable levels. Additional alternative source options include trucking in potable water, purchasing water rights, and temporarily relying on bottled water.

Figure 2-1 Selective Well Screening Using a Packer/Plug.

Modification of impacted source wells can allow for withdrawal of water with lower nitrate levels by limiting screened intervals to regions of better water quality. Down hole remediation requires characterization of the water quality profile to determine the screening depth range of the higher water quality. Specialized monitoring equipment and techniques are available that can be used without removing pumps (BESST Inc., 2008). With water profile characterization, existing wells can be selectively screened using a packer/plug to limit withdrawal from unwanted regions (Figure 2-1 ).
The City of Ceres, CA is in the process of drilling new wells in part to avoid the need for nitrate treatment; well modification has also been implemented to avoid water with high nitrate levels (Cannella, 2009).

2.4 Blending

The dilution of a nitrate impacted source with an alternate low nitrate source can be a cost effective option to produce compliant water; this is known as blending and can be applied independently or with treatment. Blending is a common practice for the production of compliant water, but relies on the availability of a low nitrate source and the consistency of nitrate levels to avoid exceedances. One drawback of adding blending to address nitrate contamination is the loss of operational flexibility. If the source used for dilution were compromised, then production would need to be stopped from both wells. Water can also be trucked in for blending purposes when a low nitrate source is unavailable locally. Based on the recent AWWA survey, 51.8% (29/56) of respondents with nitrate impacted sources selected blending as the option to address nitrate contamination (Weir & Roberson, 2010, Weir and Roberson, 2011). In Germany, “most water utilities...affected by high nitrate concentrations do blending of high-nitrate and low-nitrate wells...to avoid treatment costs” (Dördelmann, 2009). When feasible, blending is a simple alternative to treatment that avoids disposal concerns and the certification requirements of treatment (WA DOH, 2005). However, disadvantages include the capital investment for accessing an alternative source and monitoring requirements to ensure consistent supply of compliant water (WA DOH, 2005).
3.0 Treatment Options for Nitrate Contaminated Potable Water

IX, RO and ED/EDR transfer nitrate ions from water to a concentrated waste stream that requires disposal. The United States Environmental Protection Agency (USEPA) lists these three processes as accepted potable water treatment methods for nitrate removal (USEPA, 2010). In contrast, through biological and chemical denitrification, nitrate is converted to reduced nitrogen species, rather than simply displaced to a concentrated waste stream that requires disposal.

A survey of nitrate treatment systems was conducted to assess the current state of nitrate treatment. The list of surveyed utilities was developed with the intention of covering a range of utilities with respect to geographic location, treatment type, population size and residual handling techniques (Table 3-1). Detailed case studies have been compiled for each of the treatment technologies where full-scale facilities have been in operation or are moving ahead with design.

A brief comparison of fundamental design considerations, advantages and disadvantages of the treatment options examined herein is listed in Table 3-2. It is important to note that the contents of Table 3-2 are not intended to provide a comprehensive set of criteria for treatment options. Other important criteria in determining the best treatment option, which are site specific and cannot be broadly generalized, include capital and O&M costs, system size (capacity), and system footprint.

IX is the most commonly used nitrate treatment method, with full-scale systems in use throughout the United States. Full-scale application of biological denitrification in potable water treatment is mainly limited to Europe and chemical denitrification methods have been investigated only at the pilot-scale. Others have provided thorough reviews of available nitrate treatment technologies (Kapoor & Viraraghavan, 1997; Soares, 2000; Shrimali & Singh, 2001); however, a recent comprehensive review of the state of nitrate treatment is absent from the literature.
Table 3-1 Utilities Included in the Case Studies.

<table>
<thead>
<tr>
<th>Case #</th>
<th>Treatment Type</th>
<th>Location</th>
<th>Capacity (gpm)</th>
<th>Avg. Influent Nitrate (mg/L as N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Ion Exchange</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Conventional ion exchange with blending</td>
<td>California</td>
<td>400</td>
<td>7-12</td>
</tr>
<tr>
<td>2</td>
<td>Conventional ion exchange with blending</td>
<td>California</td>
<td>400</td>
<td>~10</td>
</tr>
<tr>
<td>3</td>
<td>Counter Current Ion Exchange (MIEX®)</td>
<td>Indian Hills, CO</td>
<td>50</td>
<td>12-16</td>
</tr>
<tr>
<td>4</td>
<td>Multiple vessel ion exchange</td>
<td>California</td>
<td>500-900</td>
<td>8-20</td>
</tr>
<tr>
<td>5</td>
<td>Multiple vessel ion exchange</td>
<td>Chino, CA</td>
<td>5000</td>
<td>9-45</td>
</tr>
<tr>
<td></td>
<td><strong>Reverse Osmosis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Reverse osmosis and blending</td>
<td>Bakersfield, CA</td>
<td>120</td>
<td>17-19</td>
</tr>
<tr>
<td>7</td>
<td>Reverse osmosis, exploring biological reduction</td>
<td>Brighton, CO</td>
<td>4600</td>
<td>11-20</td>
</tr>
<tr>
<td>8</td>
<td>Reverse osmosis and blending</td>
<td>Arlington Desalter, Riverside, CA</td>
<td>4583</td>
<td>10-20</td>
</tr>
<tr>
<td></td>
<td><strong>Combined Reverse Osmosis and Ion Exchange</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Reverse osmosis, ion exchange and blending</td>
<td>Chino Desalter I, Chino, CA</td>
<td>4940 (RO), 3400 (IX)</td>
<td>32-65</td>
</tr>
<tr>
<td>10</td>
<td>Reverse osmosis, ion exchange and blending</td>
<td>Chino Desalter II, Mira Loma, CA</td>
<td>4167 (RO), 2778 (IX)</td>
<td>15-48</td>
</tr>
<tr>
<td></td>
<td><strong>Electrodialysis (ED/EDR/SED)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Electrodialysis Reversal (EDR)</td>
<td>Spain</td>
<td>3,260 (each, 2 systems)</td>
<td>18</td>
</tr>
<tr>
<td>12</td>
<td>Selective Electrodialysis (SED) - Nitron</td>
<td>Israel</td>
<td>310</td>
<td>19-20</td>
</tr>
<tr>
<td></td>
<td><strong>Biological Denitrification</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Implementing fluidized bed biological reduction</td>
<td>Rialto, CA</td>
<td>2000-4000</td>
<td>17-19</td>
</tr>
<tr>
<td>14</td>
<td>Implementing fixed bed biological reduction</td>
<td>Riverside, CA</td>
<td>1670</td>
<td>10-20</td>
</tr>
</tbody>
</table>
### Table 3-2 Potable Water Treatment Options for Nitrate Management (adapted from WA DOH, 2005).

<table>
<thead>
<tr>
<th>Full Scale Systems</th>
<th>Ion Exchange</th>
<th>Reverse Osmosis</th>
<th>Electro dialysis</th>
<th>Biological Denitrification</th>
<th>Chemical Denitrification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Type</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Common Water Quality Design Considerations</td>
<td>Sulfate, iron, manganese, total suspended solids (TSS), metals (e.g., arsenic), hardness, organic matter</td>
<td>Turbidity, iron, manganese, SDI, particle size, TSS, hardness, organic matter, metals (e.g., arsenic)</td>
<td>Turbidity, iron, manganese, TSS, hydrogen sulfide, hardness, metals (e.g., arsenic)</td>
<td>Temperature and pH, anoxic conditions</td>
<td>Temperature and pH</td>
</tr>
<tr>
<td>Pretreatment Needs</td>
<td>Pre-filter, address hardness</td>
<td>Pre-filter, address hardness</td>
<td>Pre-filter, address hardness</td>
<td>pH adjustment, nutrient and substrate addition, need for anoxic conditions</td>
<td>pH adjustment</td>
</tr>
<tr>
<td>Post-treatment Needs</td>
<td>pH adjustment</td>
<td>pH adjustment</td>
<td>pH adjustment</td>
<td>Filtration, disinfection, possible substrate adsorption</td>
<td>pH adjustment, iron removal, potential ammonia control</td>
</tr>
<tr>
<td>Waste/Residuals Management</td>
<td>Waste brine</td>
<td>Concentrate</td>
<td>Concentrate</td>
<td>Sludge/biosolids</td>
<td>Waste media, Iron sludge</td>
</tr>
<tr>
<td>Start-up Time</td>
<td>Minutes</td>
<td>Minutes</td>
<td>Minutes</td>
<td>Initial plant startup: Days to weeks After reaching steady state: Minutes</td>
<td>Minutes</td>
</tr>
<tr>
<td>Water Recovery</td>
<td>Conventional (97%) Low brine (Up to 99.9%)</td>
<td>Up to 85%</td>
<td>Up to 95%</td>
<td>Nearly 100%</td>
<td>Not demonstrated full scale</td>
</tr>
<tr>
<td>Advantages</td>
<td>Nitrate selective resins, common application, multiple contaminant removal</td>
<td>Multiple contaminant removal, desalination (TDS removal)</td>
<td>Multiple contaminant removal, higher water recovery (less waste), desalination, unaffected by silica</td>
<td>No waste brine or concentrate, nitrate reduction rather than transfer to a waste stream, high water recovery, and potential for multiple contaminant removal</td>
<td>No waste brine or concentrate, nitrate reduction rather than transfer to a waste stream, and potential for multiple contaminant removal</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Potential for nitrate peaking, high chemical use (salt), brine waste disposal, potential for disinfection byproduct (DBP) formation (e.g., NDMA)</td>
<td>Membrane fouling and scaling, lower water recovery, operational complexity, energy demands, waste disposal</td>
<td>Energy demands, operational complexity, waste disposal</td>
<td>Substrate addition, potentially more complex, high monitoring needs, possible sensitivity to environmental conditions, risk of nitrite formation (potential incomplete denitrification), post-treatment to address turbidity standards and 4-log virus removal (state dependent)</td>
<td>Inconsistency of nitrate reduction, risk of nitrite formation (potential incomplete denitrification), reduction to ammonia, lack of full scale systems, pH and temperature dependence, possible need for iron removal</td>
</tr>
</tbody>
</table>
3.1 Ion Exchange (IX)

As the most commonly used method for the removal of nitrate in potable water treatment, IX has been widely researched, with numerous full-scale installations in operation. With the potential for multiple contaminant removal, IX can also be used to address other water quality concerns including arsenic, perchlorate, selenium, chromium (total and chromium-6), and uranium (AWWA, 1990 and Boodoo, 2004). Selected IX installations used for nitrate treatment in the United States are listed in Table 3-3.

Table 3-3 Selection of Full Scale Ion Exchange Installations for Nitrate Removal.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Year Installed</th>
<th>Influent nitrate (mg/L as N)</th>
<th>Capacity (MGD)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellsworth, MN</td>
<td>1994</td>
<td>-</td>
<td>0.047</td>
<td>MN Dept. of Ag. (N.D.)</td>
</tr>
<tr>
<td>Clear Lake, MN</td>
<td>1995</td>
<td>-</td>
<td>0.047</td>
<td>MN Dept. of Ag. (N.D.)</td>
</tr>
<tr>
<td>Adrian, MN</td>
<td>1998</td>
<td>-</td>
<td>0.129</td>
<td>MN Dept. of Ag. (N.D.)</td>
</tr>
<tr>
<td>Edgerton, MN</td>
<td>2002</td>
<td>-</td>
<td>0.137</td>
<td>MN Dept. of Ag. (N.D.)</td>
</tr>
<tr>
<td>McCook, NE</td>
<td>2006</td>
<td>Up to 28.27</td>
<td>6.8</td>
<td>Contaminant Removal News (2007)</td>
</tr>
<tr>
<td>La Crescenta, CA</td>
<td>1987</td>
<td>15.08-21.54</td>
<td>2.7</td>
<td>Guter (1995)</td>
</tr>
<tr>
<td>Grover City, CA, 3 wells</td>
<td>-</td>
<td>17.23-28</td>
<td>2.3</td>
<td>Guter (1995)</td>
</tr>
<tr>
<td>Des Moines, IA</td>
<td>1992</td>
<td>Up to 11.85</td>
<td>10</td>
<td>Des Moines Water Works, Rash (1992)</td>
</tr>
<tr>
<td>Glendale, AZ: full scale pilot</td>
<td>2010</td>
<td>Up to 40</td>
<td>10</td>
<td>Meyer et al. (2010), See also Clifford et al. (1987)</td>
</tr>
<tr>
<td>Indian Hills, CO</td>
<td>2009</td>
<td>10-16</td>
<td>0.072 (design)</td>
<td>See Case Study.</td>
</tr>
</tbody>
</table>

Due to its common application, the investigation of IX for the removal of nitrate is prevalent in the literature (Yoon et al., 2001; Chabani et al., 2006; Samatya et al., 2006; Clifford, 2007; Meyer et al., 2010; Clifford et al., 2010). Kapoor & Viraraghavan (1997) provide an extensive review of IX research up to 1997. Modifications of conventional IX have led to the emergence of more efficient IX processes including multiple vessel configurations, counter current configurations, the use of specialized resins, improved hydraulics, and weak base anion exchange (WBA IX).
3.1.1 Conventional Ion Exchange

Conventional IX utilizes a strong base anion exchange resin. In accordance with Figure 3-1, raw water passes through pretreatment to remove suspended solids and to address other constituents capable of fouling the resin. The nitrate laden treatment stream then enters the ion exchange vessel. Upon contacting the resin, nitrate displaces chloride at surface sites, removing nitrate from the water.

**Figure 3-1 Conventional Ion Exchange Schematic.**

This technique is similar to a water softener, which replaces the divalent cations of hard water (Mg$^{2+}$ and Ca$^{2+}$) with a monovalent cation (Na$^+$). Eqn. 1 depicts the transfer of ions, with $R$ as the resin surface site.

$$R-Cl + NO_3^- \rightarrow R-NO_3^- + Cl^- \quad \text{(Eqn. 1)}$$

To prevent nitrate breakthrough, regeneration is necessary when the resin is exhausted of chloride ions (chloride has been displaced at the majority of surface sites). The media is backwashed with a high salt solution (0.5 – 3 M, Clifford, 2007) to reverse the process, resulting...
in a brine waste stream high in nitrate and other concentrated ions (Eqn. 2). Leaving nitrate behind, treated water exits the ion exchange vessel and passes on to post-treatment for stabilization and disinfection.

\[
\text{R-NO}_3^- + \text{Cl}^- \rightarrow \text{R-Cl} + \text{NO}_3^-(\text{Eqn. 2})
\]

The relative affinity of common anions for conventional anion exchange resin is SO\(_4^{2-}\) > NO\(_3^-\) > Cl\(^-\) > HCO\(_3^-\) (Bae et al., 2002 and Clifford et al., 2010). If generic resins are not regenerated soon enough, sulfate displacement of nitrate in the resin can lead to nitrate release from the resin to the treatment stream (Eqn. 3). This is known as nitrate dumping, nitrate peaking and chromatographic peaking and is further discussed below.

\[
2\text{R-NO}_3^- + \text{SO}_4^{2-} \rightarrow \text{R}_2\text{SO}_4^- + 2\text{NO}_3^-\text{ (Eqn. 3)}
\]

Due to the stronger affinity of the sulfate ion for generic anion exchange resins, nitrate selective resins have been developed for which the order of affinity is NO\(_3^-\) > SO\(_4^{2-}\) > Cl\(^-\) > HCO\(_3^-\) (Guter, 1982 and Guter, 1995). Important factors in resin selection are the exchange capacity\(^1\) and selectivity coefficient\(^2\) of the resin and the rate of ion transfer (kinetics\(^3\)).

**Detailed case studies of conventional IX plants are included in section 3.1.7.**

### 3.1.2 Ion Exchange - Design Considerations

Various tools are available to assist with IX system design including Dow’s CADIX (Computer Assisted Design for Ion Exchange) (Dow, 2010b) and Lenntech’s Ion Exchange calculator (Lenntech, 2009b.) Table 3-4, summarizes key design considerations in the application of conventional IX to nitrate removal from potable water.

---

1 Exchange capacity: The exchange capacity is a measure of how many ions the resin can capture per unit volume.

2 Selectivity coefficient: The selectivity coefficient of a resin refers to the relative affinity of resin surface sites for a particular ion, in this case nitrate.

3 Kinetics: The term kinetics refers to the rate of a reaction. The rate that nitrate displaces chloride on the resin is important for efficient treatment and can be affected by competing ions.
Table 3-4 Summary of Design Considerations for Conventional IX.

| Resin Selection | • Generic SBA resins for maximum exchange capacity (for low sulfate)  
|                 |   o Less expensive than nitrate selective resins  
|                 |   o Less frequent regeneration due to higher capacity (in the absence of co-contaminants)  
|                 |   o Nitrate dumping potential  
|                 | • Nitrate selective resins to avoid nitrate dumping (for high sulfate)  
|                 |   o More expensive than generic resins  
|                 |   o Longer bed life  
|                 |   o More nitrate removed per unit of waste brine  
| Pretreatment    | • Filtration to remove iron, manganese, TSS and organic matter to prevent resin fouling  
|                 | • Water softening (anti-scalant, acid or water softener) to prevent scaling  
|                 | • Dechlorination to prevent resin oxidation\textsuperscript{4}  
| Post-Treatment  | • Chloride:alkalinity ratio and dezincification\textsuperscript{5}  
|                 | • Chloride:sulfate ratio and galvanic corrosion\textsuperscript{6}  
|                 | • Potential pH adjustment and restoration of buffering capacity to avoid corrosion  
| Chemical Usage  | • pH adjustment (caustic soda or soda ash)  
|                 | • Regenerant brine, salt consumption  
| O&M             | • Frequency of regeneration depends on water quality and resin type  
|                 | • Fresh brine preparation and waste disposal  
|                 | • Resin loss and replacement: 3-8 year lifetime (WA DOH, 2005 and Dow, 2010c)  
|                 | • Continuous or frequent monitoring of nitrate levels  
|                 | • Backwashing to dislodge solids  
| System Components | • Fixed bed versus Continuous regeneration  
|                 | • Key system configuration parameters are system flow rate, bed swelling, bed depth, backwash flow rate, and rinse requirements  
|                 |   o Vessels in parallel or in-series  
|                 |   o Co-current or counter-current regeneration  
| Waste Management and Disposal | • Significant cost of waste brine disposal is of greatest concern for inland systems  
|                 | • Close proximity to coastal waters is beneficial for brine disposal  
|                 | • Management options can include sewer or septic system, drying beds, trucking off-site, coastal pipeline, deep well injection and advanced treatment  
|                 | • Disposal options can be limited by waste brine water quality (e.g., volume, salinity, metals and radionuclides)  
|                 | • Optimization of recycling and treatment of waste brine is desirable  
| Limitations     | • Need to manage resin fouling  
|                 |   o Hardness, iron, manganese, suspended solids, organic matter, and chlorine  
|                 | • Competing ions (especially sulfate)  
|                 | • Disposal of waste brine  
|                 | • Possible role of resin residuals in DBP formation  

\textsuperscript{4} The resin can be degraded by oxidation; the functional amine groups on the resin surface are susceptible to oxidation which can lead to diminished capacity (Dow, 2010d).

\textsuperscript{5} As nitrate and other anions displace chloride on the resin, chloride is released to the product water, leading to the potential for taste issues and dezincification (Kapoor & Viraraghavan, 1997). Dezincification refers to the ability of product water to dissolve zinc from brass and is dependent on the ratio of chloride to alkalinity (> 0.5 can be problematic). By restoring alkalinity, the dezincification potential can be minimized.

\textsuperscript{6} Galvanic corrosion can result in the release of lead from brass and galvanized solder-copper connections and is associated with a high ratio of chloride to sulfate (> 0.58 can be problematic) (Edwards & Triantafyllidou, 2007 and Edwards et al., 1999).
3.1.2.1 Water Quality

Raw water quality is a key factor in the efficiency of an IX system, impacting resin selection, pretreatment and post-treatment needs, regeneration efficiency, chemical usage, and waste disposal. Important water quality parameters include the presence of competing ions (predominantly sulfate), alkalinity, hardness, iron, and manganese.

Selection of the appropriate resin for a given system depends directly on source water quality. In the presence of high levels of co-contaminants, nitrate selective resins may be necessary rather than generic resins. Both strong base anion resin (SBA) and weak base anion resin (WBA) can be suitable for nitrate removal from potable water. The latter will be addressed separately. The two standard types of SBA resins deviate in their functional groups. Anion exchange is dependent on the trimethylamine groups of the SBA Type I resin and the dimethylethanolamine groups of the SBA Type II resin (Helfferich, 1995).

Nitrate selective resin was invented in the early 1980’s by Gerald Guter (Guter, 1982, see related patent: Guter, 1983). Clifford & Weber (1978 and 1983) contributed to the development and characterization of these resins with their research on resin selectivity (Clifford et al., 2010). Nitrate selective resins rely on different functional groups than Type I and Type II SBA resins. Nitrate selectivity is attributed to the increased hydrophobicity and site spacing of exchange sites due to the triethyl, tripropyl and tributyl functional groups of nitrate selective resin (Clifford & Weber, 1978; Guter, 1982; and Clifford et al., 2010). The use of nitrate selective resin avoids the problem of nitrate peaking (i.e., nitrate dumping or chromatographic peaking), typically caused by the greater affinity of generic resins for sulfate.

It is important to note the distinction between nitrate peaking and nitrate breakthrough. As nitrate displaces chloride on the resin, the nitrate capacity of the resin is gradually exhausted leading to increasing effluent nitrate levels until influent levels are reached. This is known as breakthrough and can occur regardless of resin type. Nitrate peaking can also occur upon exhaustion of the resin capacity for nitrate. However, with nitrate peaking, the nitrate on the resin is displaced by sulfate, thereby increasing the effluent nitrate concentration to levels above that of the raw water (Clifford et al., 2010). The peak in nitrate concentration is due to the combination of the influent nitrate ions and the nitrate ions that are coming off of the resin via sulfate displacement.
Under low sulfate conditions, the use of generic SBA resins is preferred, due to their larger exchange capacity. As the ratio of sulfate to nitrate increases, the use of nitrate selective resins avoids possible nitrate peaking, minimizing the risk of MCL exceedance and the need for more frequent regeneration. However, with the highest nitrate selectivity, regeneration efficiency can decrease, increasing chemical use. With a stronger affinity for nitrate, the removal of nitrate from the resin in regeneration is more difficult because nitrate is more strongly bound (Dow, 2010c). Nitrate selective resins are more costly than the generic option (Water Quality Products, 2003), but under appropriate conditions the use of regenerant can be minimized and bed life can be increased significantly with their use. Different system configurations have been implemented as an alternative to the use of nitrate selective resins to address the problem of co-contaminants and the risk of nitrate peaking (Clifford, 2010). (See System Layout and Site Considerations.) In the consideration of IX for multiple contaminant removal, the selection of the most appropriate resin depends in part on the type and concentration of co-contaminants. Modeling and column or pilot testing is important to determine appropriate design parameters and to design treatment based on a full life cycle analysis of costs.

Upstream of the IX vessels, pretreatment of source water may be necessary to avoid resin fouling (WA DOH, 2005 and Water Quality Products, 2003). Potential constituents of concern include organic matter, turbidity, total suspended solids (TSS), sand and metals, primarily iron and manganese (WA DOH, 2005; Water Quality Products, 2003; and Kapoor & Viraraghavan, 1997). Pre-filtration is typically used to remove these constituents; however, additional pretreatment methods may be used. For example, coagulation/flocculation and filtration may be necessary for surface waters. “If the combination of iron, manganese, and other metals exceeds 0.1 mg/L, pretreatment will likely be required (Health Education Services, 1997)” (WA DOH, 2005). Hard, alkaline water can lead to resin scaling due to calcium and magnesium accumulation; pH adjustment or water softening can be used to prevent resin scaling (Water Quality Products, 2003). Created by Wolfgang Holl, the carbon dioxide regeneration of ion exchange (CARIX) process combines anion and cation exchange (Holl, 1995). The CARIX process enables simultaneous removal of cations (for hardness reduction) and anions through the combination of a weak acid cation exchanger and a strong base anion exchanger.
Resin exposure to disinfectants (chlorine and chloramines) should be avoided to prevent resin oxidation and the possible release of disinfection by-products, specifically nitrosamines (Kemper et al., 2009). Disinfection byproducts (DBPs) are potentially cancer-causing compounds that can be formed through a reaction of disinfection chemicals like chlorine and chloramines with organic matter. Due to the amine functional groups of anion exchange resins, “these resins may serve as precursors for nitrogenous disinfection by-products, such as nitrosamines, nitramines, and halonitromethanes” (Kemper et al., 2009). Recent research suggests that the risk of DBP formation is higher with the use of new resin; however, precursors can be a problem with downstream chloramine use or with upstream disinfection (See Kemper et al., 2009 in Table A.1 of the Appendix). Magnetic ion exchange resin is an exception as its primary purpose is to remove organic carbon and limit DBP formation (Boyer & Singer, 2006) (See the MIEX® process in section 3.1.6.1).

IX can reduce alkalinity due to removal of bicarbonate. To prevent corrosion in downstream pipes, the product water pH and buffering capacity may need to be increased\(^7\). Soda ash can be added to the regenerant brine to load a portion of the resin sites with bicarbonate rather than chloride. This can restore some alkalinity to the water as bicarbonate is released from the resin when displaced by nitrate and other anions in the treatment stream (Water Quality Products, 2003). To minimize the need for caustic addition in post-treatment, an upstream atmospheric degasifier for carbon dioxide removal can be added during pretreatment (Dow, 2010).

As nitrate and other anions displace chloride on the resin, chloride is released to the product water, leading to the potential for taste issues, dezincification, and galvanic corrosion. Dezincification refers to the ability of product water to dissolve zinc from brass and is dependent on the ratio of chloride to alkalinity (\(> 0.5\) can be problematic, according to Kapoor & Viraraghavan (1997)). By restoring alkalinity, the dezincification potential can be minimized. Galvanic corrosion can result in the release of lead from brass and galvanized solder-copper

\(^7\) It is important to note the relationship between alkalinity and pH. Alkalinity is a measure of buffering capacity or the resistance to changes in pH. Demineralized water or water with a low buffering capacity will be susceptible to more dramatic pH changes and is considered unstable. The pH of acidic product water should be adjusted and the buffering capacity of demineralized product water should be restored to avoid corrosion downstream and the potential for lead and copper challenges.
connections and is associated with a high ratio of chloride to sulfate (> 0.58 can be problematic) (Edwards & Triantafyllidou, 2007 and Edwards et al., 1999). It is important to consider the potential downstream impact of subtle water quality changes caused by treatment.

3.1.2.2 System Layout and Site Considerations

The IX system can be operated using a fixed bed or as a continuous system. Details of modifications to conventional fixed bed systems are provided below. Key parameters in vessel sizing and system configuration are system flow rate, bed swelling, bed depth, backwash flow rate, and rinse requirements (Dow, 2010). Regeneration can be designed in a co-current or counter-current configuration. Vessels can be operated in parallel or in-series for redundancy, to maximize removal efficiency per regeneration cycle, to address nitrate peaking and to consistently produce water with limited variation in water quality parameters (Clifford et al., 2010).

3.1.2.3 Residuals Management and Disposal

Management of waste brine can be costly. Options include discharge to a sewer or septic system, waste volume reduction using drying beds, trucking to an off-site approved disposal location, ocean discharge through a coastal pipeline, deep well injection, and advanced treatment. Water quality characteristics of the waste brine (e.g., volume, salinity, metals and radionuclides) can affect the feasibility and costs of disposal options. Proximity and access to coastal waters can be a significant factor in determining the burden of brine disposal. Generally, disposal is of greatest concern to inland communities. Although other removal technologies (RO and ED) require concentrate disposal, because IX requires the addition of salt for resin regeneration, the waste stream consists of not only the nitrate and other ions that have been removed from the water, but also the spent brine solution used in regeneration. The high cost of nitrate laden brine disposal has led to research into optimization of recycling and treatment of this waste stream. Partial regeneration and reuse of treated brine for multiple regeneration cycles can minimize the volume of waste while maximizing regeneration efficiency (Clifford, 2007 and Clifford et al., 2010). Application of IX systems coupled with biological, chemical, or catalytic denitrification enables removal of nitrate from waste brine,
with reduction to nitrogen gas. The electrochemical destruction of nitrate in waste brine is also being explored. Several combined configurations of interest are discussed below in a section devoted to Brine Treatment Alternatives and Hybrid Treatment Systems.

3.1.2.4 Maintenance, Monitoring and Operational Complexity

Regeneration frequency will depend on pretreatment measures, water quality and the type of resin used (WA DOH, 2005). The typical amount of brine waste compared to water produced can range from ~3.0% for conventional systems (Clifford, 2007) to ~0.5% for low brine systems (Calgon Carbon Corporation, 2007, discussed below). A constant supply of brine must be available for resin regeneration and waste brine requires appropriate storage and disposal. Resin loss can be controlled by adjusting the backwash flow rate and adding screens (Keller, 2000). Resin life will also depend on water quality and pretreatment measures; resin replacement may be required after 3-8 years (WA DOH, 2005 and Dow, 2010c). To ensure the production of compliant water, continuous or frequent monitoring of nitrate levels is necessary.

In addition to resin regeneration, backwashing is used to dislodge solids and “resin fines” (Dow, 2010). In comparison with alternative treatment options, IX requires limited O&M with high feasibility of automation and low operational complexity.

3.1.3 Ion Exchange - Cost Considerations

For optimal operation of an IX system, the fundamental objective is to maximize regeneration efficiency, while meeting necessary potable water guidelines. Factors affecting system cost include facility size (flow rate), source water quality (including nitrate concentration), environmental factors (temperature), and target effluent nitrate concentration. Disposal of waste brine is commonly a significant portion of O&M costs.

Capital costs for IX include land, housing, piping, storage tanks, O&M equipment, vessels, resin, preliminary testing (pilot studies), permits, and training. O&M costs include resin replacement (due to loss or degradation), resin disposal, brine disposal or treatment, chemical use (salt, anti-scalant, pH adjustment), repair and maintenance, power and labor.

Published cost information from existing IX installations is listed in Table 3-5. Costs have been adjusted to 2010 dollars, unless indicated otherwise. Costs can be difficult to assess due to
inconsistencies in how cost information is reported. Comparison of IX costs is not always valid due to differences in influent water quality parameters, system size, waste management options, and system configuration. Published costs do not always include comparable information. It would be inappropriate to compare the O&M costs of a facility that excludes disposal costs with others that include this information. The listed cost information is provided as an approximate range of costs for specific facilities. Costs for implementing IX may be very different from those listed here. A thorough cost analysis of design parameters for specific locations would be required for accurate cost estimation. The information gathered through the questionnaire includes detailed costs associated with the unique case studies included in this analysis.

**Table 3-5 Selected Published Costs* of Ion Exchange Systems for Nitrate Removal.**

<table>
<thead>
<tr>
<th>System Flow**</th>
<th>&lt; 0.5 MGD</th>
<th>0.5 – 5 MGD</th>
<th>5+ MGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annualized Capital Cost ($/1000 gal)</td>
<td>0.37 – 1.21 [1]</td>
<td>0.28 – 0.94 [2, 3]</td>
<td>0.28 – 0.61 [3, 4, 5]</td>
</tr>
<tr>
<td>O&amp;M Cost ($/1000 gal)</td>
<td>0.60 – 4.65 [1]</td>
<td>0.46 – 1.25 [2, 3]</td>
<td>0.37 – 0.87 [3, 4, 5]</td>
</tr>
<tr>
<td>Total Annualized Cost ($/1000 gal)</td>
<td>0.97 – 5.71 [1]</td>
<td>0.74 – 2.19 [2, 3]</td>
<td>0.65 – 1.44 [3, 4, 5]</td>
</tr>
</tbody>
</table>

*Costs have been adjusted to 2010 dollars with 7% interest over 20 years, unless indicated otherwise (below).
**When available, costs are based on actual system flow rather than design capacity.
[1] Minnesota Department of Agriculture (N.D.), not adjusted to 2010 dollars, 20 year amortization without interest.

### 3.1.4 Ion Exchange - Selected Research

A large body of research has focused on IX. Table A.1 of the Appendix is a list of recent studies relevant to nitrate removal from potable water. Given the many years of successful full scale operating experience with IX, current applied research is focused on brine recycling efficiency, the optimization of waste management, and improvements in resin capacity and selectivity, to improve efficiency and reduce costs.

### 3.1.5 Ion Exchange - Summary of Advantages and Disadvantages

A summary of advantages and disadvantages of IX in comparison with other treatment options is listed in Table A.6 of the Appendix. Significant advantages of IX include years of industry experience, multiple contaminant removal, selective nitrate removal, financial feasibility, use in small and large systems, and the ability to automate. Disadvantages include the costly disposal
of waste brine, the potential for nitrate dumping and resin fouling, the possible need for pH adjustment, the potential for hazardous waste generation (i.e. brine with traces of co-contaminants like arsenic and chromium), and the possible role of resin residuals in DBP formation (Kemper et al., 2009).

3.1.6 Modifications to Conventional Ion Exchange

Modifications of conventional IX have led to the emergence of low-brine IX processes including magnetic ion exchange (MIEX®), ion exchange separation (ISEP®), Envirogen (formerly Basin Water) systems, and weak base ion exchange (WBA IX). Despite their potential advantages, it is important to note that proprietary technologies may have inherent disadvantages, such as a lack of flexibility to use better technology when it becomes available, vulnerability if the manufacturer goes out of business or discontinues supporting the product, and a lack of competition to keep O&M costs down.

3.1.6.1 Counter Current Flow with Specialized Resin

Magnetic ion exchange technology (MIEX®), developed by Orica Watercare, offers a low brine alternative to conventional IX, using a unique SBA Type I resin. The MIEX® process (Figure 3-2) differs from conventional IX in that the resin is fluidized in a contactor with spent resin removed from the contactor for regeneration outside of the process water stream and then returned to the contactor. This is in contrast to conventional IX, where the resin is stationary. Unlike conventional IX, the MIEX® fluidized bed process is tolerant of suspended solids and low levels of oxidants.
The minimization of waste brine is accomplished through frequent batch regeneration. The magnetized resin encourages agglomeration of loaded resin particles, resulting in faster settling. Loaded resin is removed from the bottom of the IX vessel and is passed to regeneration, while regenerated resin is added at the top of the IX vessel. This configuration removes the risk of nitrate peaking because clean resin, added at the end point of the system, captures any displaced nitrate, while competing ions, such as sulfate can be removed early on in the resin vessel. The MIEX® process has been proven to effectively address various water quality concerns including nitrate, organic carbon, arsenic, chromium-6 and perchlorate (Boyer & Singer, 2006; Humbert et al., 2005; and Seidel et al., 2004. See also Orica Watercare, N.D.).
A detailed case study of a MIEX® treatment plant in Indian Hills, CO is included in section 3.1.7.

3.1.6.2 Improved Hydraulics and Nitrate Selective Resins

The Layne Christensen Company and Rohm and Haas offer their Advanced Amberpack® system which utilizes nitrate selective resins and their patented Fractal Distribution Technology to increase the treated water volume and decrease the waste brine. Nitrate selective resins have a greater affinity for nitrate than non-selective resins resulting in an improvement in removal efficiency, especially in waters where the sulfate to nitrate ratio is greater than 1.

The distributor system is designed to provide uniform flow through the ion exchange vessels in both treatment and regeneration modes. As a result of the uniform flow the exchange capacity of the resin can be maximized while the brine and rinse values can be minimized, thus increasing the water efficiency of the system (Rohm and Haas Company, 2007).

3.1.6.3 Multiple Vessel Carousel Configuration

Calgon Carbon’s Continuous Ion Exchange Separation System (ISEP® System) utilizes a carousel configuration. This configuration has the potential to avoid downtime for regeneration, minimize the amount of resin needed, and maximize regeneration efficiency. Illustrated in Figure 3-3, multiple resin vessels are rotated from active treatment to resin regeneration and rinsing and back to active treatment. The countercurrent system can provide consistent product water, operating uninterrupted with up-flow regeneration and down-flow treatment. The vessels (Table 3-3) rotate in the opposite direction of the water movement (Table 3-4). This configuration results in five zones within the system (Calgon Carbon Corporation, 2004). In “the adsorption wash zone” several vessels are washed in series with clean water. The effluent is added to the treatment stream to avoid loss. In “the feed zone” the feed stream is passed through two stages of 10 parallel vessels and product water is collected.
Figure 3-3 Vessel Rotation in Calgon Carbon’s Countercurrent ISEP® System (Calgon Carbon Corporation, 2004).

**ISEP® Illustration**

[Diagram showing vessel rotation and flow paths]
Figure 3-4 Example of Flow Through the ISEP® System (Calgon Carbon Corporation, 2004).
In “the entrainment rejection zone” a portion of the product water is passed through two vessels in series for reuse as rinse water. Regenerant brine is rinsed through two in series vessels in “the rinse zone.” Lastly, regeneration occurs through three in series vessels with the addition of regenerant brine in “the regeneration zone.”

**A detailed case study of an ISEP® treatment plant in Chino, CA is included in section 3.1.7.**

### 3.1.6.4  Multiple Vessel Staggered Configuration

Envirogen Technologies, Inc., formerly Basin Water, Inc., offers proprietary IX systems using multiple beds operated in a staggered design (Figure 3-5). Such a configuration has the potential to maximize resin capacity and minimize waste and chemical use.

**Figure 3-5  Example of an Envirogen Multiple Bed Proprietary Anion Exchange System (Envirogen, N.D.a).**

Envirogen’s low brine IX system has been successfully implemented for nitrate and uranium removal in San Bernardino County, CA (Envirogen, 2010). Delivering 2 MGD with nitrate levels reduced from 10.77-12.92 mg/L as N (50-60 mg/L as nitrate) to 7.54 mg/L as N (35 mg/L as...
nitrate) and a system footprint of 50’ X 50’, the installation resulted in recovery of a well that had been previously decommissioned. Envirogen is contracted to handle all operation and maintenance, including waste disposal.

In Yucca Valley, CA, nitrate treatment was required due to over pumping and the resulting intrusion of septic system contaminated waters. An Envirogen IX system was installed to provide 2.8 MGD. With treatment, nitrate concentrations are decreased from 12.49 mg/L as N (58 mg/L as nitrate) to 4.31 mg/L as N (20 mg/L as nitrate) with 50% blending and a 0.3% waste rate (0.15% net) (Envirogen, N.D.b).

*A detailed case study of an Evirogen low-brine IX treatment plant in California is included in section 3.1.7.*

### 3.1.6.5 Weak Base Anion Exchange (WBA IX)

Weak base anion exchange (WBA IX), an emerging technology, can be an effective option for nitrate removal from potable water. Highly pH dependent, nitrate removal using WBA IX is governed by Eqn. 5 (Applied Research Associates, N.D.). While SBA IX resin can remove nitrate by splitting nitrate salts, WBA IX resin removes strong acids (Remco Engineering). First, acid addition protonates the WBA resin (Eqn. 4). Next, the positively charged resin sites remove anions, like nitrate, from the treatment stream (Eqn. 5).

\[
R-\text{NH}_2 + H^+ \rightarrow R-\text{NH}_3^+
\]

(Eqn. 4)

\[
R-\text{NH}_3^+ + \text{NO}_3^- \rightarrow R-\text{NH}_3-\text{NO}_3
\]

(Eqn. 5)

Resin regeneration occurs by neutralizing the resin, in accordance with Eqn. 6. Rather than the high salt solution used to regenerate SBA resins, weak bases are used to neutralize the WBA resin.

\[
R-\text{NH}_3-\text{NO}_3 + \text{Na}^+\text{OH}^- \rightarrow R-\text{NH}_2 + \text{HOH} + \text{Na}^+\text{NO}_3^-
\]

(Eqn. 6)

As discussed in previous sections, the use of SBA IX resin results in a high-nitrate brine waste stream. Due to the high salt content, the nitrate in the waste stream generally cannot be beneficially reused. However, with the use of alternative weak bases for regeneration (Eqns. 7 and 8), the waste stream does not have a high salt content and can sometimes be recycled as fertilizer (NH$_4$NO$_3$ and Ca(NO$_3$)$_2$) (Clifford, 2007).
The use of WBA resins is more operationally complex than the use of SBA resins. Chemical use includes acids and bases, the system is susceptible to corrosion and pH adjustments are more significant. Adjustment of influent pH to between 3 and 6 is necessary, with subsequent product water pH adjustment as well (Clifford, 2007). WBA resins can also be more sensitive to temperature, with one resin having a maximum operating level of 95°C (Dow, 2010), but this should not impact their use with municipal drinking water treatment. Regeneration of WBA resin is more efficient than that of the SBA resin of conventional IX; regenerant waste volumes are minimized and waste products can sometimes be recycled as fertilizer (Clifford, 2007 and ARA & Purolite, N.D.a).

Weak Base Ion Exchange for Nitrate, or the “WIN” Process, was developed by Applied Research Associates, Inc. (ARA) and The Purolite Company (ARA & Purolite, N.D.b) as a treatment option that can be less costly and more efficient, with significantly lower waste volumes, than conventional SBA IX (Figure 3-6).
As an emerging technology, available information is limited to that provided by the manufacturers. The process consists of a pretreatment step to decrease pH, followed by ion exchange vessels in series, and post-treatment to increase pH. The manufacturer states, “The volume of nitrate-containing effluent from the WIN process is typically less than 0.2% of the treated water and, in some cases, may be land applied as fertilizer” (ARA & Purolite, N.D.b). As discussed above, the use of SBA IX resin results in a high-nitrate brine waste stream. Due to the high salt content, the nitrate in the waste stream generally cannot be beneficially reused. However, with the use of alternative weak bases for regeneration, the waste stream does not have a high salt content and could potentially be recycled as fertilizer.

3.1.7 Ion Exchange - Case Studies

3.1.7.1 Conventional Ion Exchange - Case Studies

The following case studies provide detailed information on the design and operation of full-scale conventional IX treatment plants for nitrate removal. Conventional IX is also used by the Chino
Basin Desalter Authority in combination with RO. Detailed case studies for the Chino Desalter are listed separately in the RO case study section.
System Description

A California utility is responsible for a system that has two groundwater supplies, one of which has nitrate at levels that exceed the MCL. The impacted well has a production capacity of 400 gpm and historical nitrate concentrations ranging from 7 mg/L to 12 mg/L of nitrate as N. The utility has implemented a blending program and installed a conventional IX treatment system in 2007 for nitrate control and treatment.

The nitrate impacted sources also have arsenic levels above the MCL of 10 µg/L which influenced the decision to install IX. IX can simultaneously remove nitrate and arsenic. The treatment system is comprised of three pressure vessels. Two vessels contain Purolite A300E for arsenic removal and the third vessel contains the nitrate selective Purolite A520E resin. The system was originally installed in 2007 and was further modified in 2009. The system is designed to decrease nitrate levels to less than 5 mg/L prior to blending. The maximum distribution system water goal for nitrate is 8 mg/L as N. To assure the system maintains the treatment goals, online nitrate analyzers have been installed at two locations, after the IX system and after blending.

Source Water Quality

- Nitrate (mg/L N)
  - Average – 8
  - Minimum – 7
  - Maximum – 12
- Co-contaminants
  - Arsenic (15 µg/L)
  - Sulfate (66 mg/L)

Treatment Technology Selection

The conventional IX system was selected to treat both nitrate and arsenic. The decision was further influenced by the ability to discharge the waste brine to a municipal sewer, a cost effective disposal option. Often technology selection is limited by the costs of brine management. If a utility has the option to dispose of the waste brine to a municipal sewer it can significantly decrease the operations and maintenance cost of the system. No other technologies were pilot tested prior to installation of the IX system.
Treatment System Parameters

- **Design Capacity**
  - 400 gpm maximum capacity

- **Pretreatment**
  - None

- **Treatment system footprint**
  - Treatment system: 30’ x 35’
  - Building footprint: None

- **Ion exchange pressure vessels**
  - Number of vessels: 3
  - Diameter of vessels: 6’
  - Height of vessels: 6’

- **Design Loading Rate**
  - 5.2 gpm/ft$^2$

- **Bed volumes prior to regeneration**
  - 345-470 (approximately 220,000-300,000 gallons treated)

- **Resin Type**
  - Purolite A200E and Purolite A520E nitrate selective

- **Previous resins used**
  - None

- **Salt Consumption**
  - 1,700 lb/week (May-Sept) and 600 lb/week (Oct-April)

- **Volume of brine generated**
  - 800 gal/vessel/backwash
  - 99.7% water efficiency

- **Monitoring**
  - Online nitrate analyzer
  - Laboratory samples

Residuals Management

The waste brine is discharged to the sewer and sent to a municipal wastewater treatment facility, with an annual cost of $12,000. There have not been any unexpected residuals that have impacted the disposal option.

Technology Benefits and Drawbacks

**Benefits**
- Ease of regeneration
- Direct-to-sewer brine disposal
- Simple, manually operated system

**Drawbacks**
- System has potential for breakthrough of nitrate or arsenic
- Time intensive operations
- Required increase in operator certification (California T-3)

Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total:</td>
<td>$350,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual O&amp;M Costs (Total with explanation or component costs)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total:</td>
<td>$66,500</td>
</tr>
<tr>
<td>Resin:</td>
<td>$13,000</td>
</tr>
<tr>
<td>Brine Disposal or Treatment:</td>
<td>$12,000</td>
</tr>
<tr>
<td>Chemicals:</td>
<td>$5,500</td>
</tr>
<tr>
<td>Repair/Maintenance (not including Labor):</td>
<td>$4,500</td>
</tr>
<tr>
<td>Power:</td>
<td>$2,500</td>
</tr>
<tr>
<td>Labor ($)</td>
<td>$28,000</td>
</tr>
</tbody>
</table>

Operational Notes

Since nitrate is an acute contaminant, the reliability of the treatment system is an utmost concern. The system is equipped with online nitrate analyzers which causes a shutdown of the treatment system when nitrate is at or above 8 mg/L as N. Additionally, the treatment system has experienced arsenic breakthrough resulting in concentrations above the MCL. The treatment system has also experienced premature nitrate breakthrough as a result of faulty distributors in the ion exchange vessels which have since been replaced.
System Description

A California water utility operates a system that has three groundwater supplies with varying amounts of nitrate contamination. Two of the wells require treatment as the nitrate concentration is at or above the 10 mg/L N MCL. The third well has nitrate ranging from 5 mg/L as N to 7 mg/L as N and does not require treatment, but is blended with the IX treated water prior to distribution.

In 2006, a conventional IX system was installed. The treatment system is comprised of three pressure vessels that contain the Rohm and Haas HP 555 ion exchange resin. Since the nitrate concentration in the impacted wells is typically at the MCL, but above the established water quality goal of 8 mg/L, a sidestream treatment approach is utilized. In sidestream treatment a portion of the flow is passed through the treatment system while the remainder is bypassed. The IX treatment results in very low nitrate concentration and allows the two streams to be combined to achieve the water quality goal. Sidestream treatment offers capital and operational costs savings.

Source Water Quality

- Nitrate (mg/L N)
  - Average – 10
- Co-contaminants
  - Sulfate

Treatment Technology Selection

IX was selected for this system because the utility was familiar with the technology from other installations. No technologies were pilot tested prior to the installation of the IX system.

Treatment System Parameters

| Design Capacity | 400 gpm maximum capacity |
| Pretreatment    | 100 mesh strainer |
|                 | 10 micron screen |
| Treatment system footprint | Treatment system: 20’ x 100’ |
|                  | Residual handling: 40’ x 100’ |
|                  | Total footprint: 60’ x 100’ |
| Ion exchange pressure vessels | Number of vessels: 3 |
|                        | Diameter of vessels: 4’ |
|                        | Height of vessels: 6’ |
| Design Loading Rate  | 10 gpm/ft² |
| Bed volumes prior to regeneration | 309 BV |
|                            | Regeneration occurs every 12.4 hours |
| Resin Type: Rohm and Haas HP 555 |
| Previous resins used: None |
| Salt Consumption: Estimated to be 32,000 lbs of salt per month |
| Volume of brine generated | 1,000 gal/vessel/backwash |
|                            | 99.2% water efficiency |
| Monitoring:                | Online nitrate analyzer |
|                            | Laboratory samples |
Residuals Management

The spent brine is held in a storage tank and ultimately disposed off site. Brine volumes are minimized by using a partial flow treatment strategy where only 400 gpm is treated by the IX system while the remaining 500 gpm bypasses the system. The untreated flow is recombined with the treated water prior to entering the distribution system.

Technology Benefits and Drawbacks

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Familiarity with technology</td>
<td>• No onsite brine disposal</td>
</tr>
<tr>
<td>• Simple, manually operated system</td>
<td>• Design flaws</td>
</tr>
<tr>
<td></td>
<td>• Inconsistent operations</td>
</tr>
<tr>
<td></td>
<td>• Potential for nitrate breakthrough</td>
</tr>
</tbody>
</table>

Treatment Technology Costs

Cost information was not included with the survey response.

Operational Notes

This particular IX system has had a series of operational challenges, many of which can be attributed to faulty engineering. Sections of exposed Schedule 80 PVC failed due to freezing, while other sections of pipe failed due to prolonged UV exposure. The brine reclaim tank experienced algal growth and was ultimately replaced with an opaque, UV-resistant tank.

The plant has experienced shut downs due to an exceedance of the nitrate MCL. Routine sampling showed distribution system nitrate concentrations above the MCL. The system utilizes an online nitrate analyzer to prevent MCL violation; however, a calibration error prevented the system from shutting down as programmed. It is believed a second failure occurred as a result of the brine saturator having a low salt concentration resulting in incomplete regeneration of the resin.

It should be noted that, due to concerns of nitrosamine release (which can be common for IX systems), the effluent of each vessel and the Point of Entry of the distribution system are tested before the system is placed in service.
3.1.7.2 Modifications to Conventional Ion Exchange - Case Studies

The following case studies provide detailed information on the design and operation of full-scale low-brine IX systems including MIEX®, ISEP®, and Envirogen (formerly Basin Water) systems.
System Description

The Indian Hills Water District (District) utilizes a groundwater well with a production capacity of approximately 50 gpm. The well has historical nitrate concentrations ranging from 12 mg/L to 16 mg/L of nitrate as N. The District has implemented the Counter-Current Ion Exchange process developed by Orica Water Care. Unlike traditional packed bed IX, the Orica process uses a Magnetic Ion Exchange (MIEX®) resin in a series of fluidized beds which allows for a reduction in brine generation.

The minimization of waste brine is accomplished through frequent batch resin regeneration. The magnetized resin encourages agglomeration of loaded resin particles, resulting in faster settling. Loaded resin is removed from the bottom of the IX vessel and is passed to regeneration, while regenerated resin is continuously added at the top of the IX vessel. This configuration reduces the risk of nitrate spiking/chromatographic peaking because clean resin, added at the end point of the system, captures any displaced nitrate, while competing ions, such as sulfate can be removed early on in the resin vessel.

Regeneration is performed continuously in small batches. Loaded resin is passed to regeneration tanks through the bottom of the IX vessel. The loaded resin is regenerated and then returned to the contactor vessel, thus maintaining a consistent ion exchange capacity in the contactor vessel. Numerous regenerations are performed on a daily basis, with the actual number of regenerations depending on the system’s flow rate.

Source Water Quality

- Nitrate (mg/L N)
  - Average – 14
  - Minimum – 12
  - Maximum – 16
- Co-contaminants
  - None noted in survey

Treatment Technology Selection

The counter current magnetic ion exchange system was selected based on the expected low levels of brine when compared to conventional packed bed IX. Prior to full scale implementation, the MIEX® process was pilot tested at Indian Hills. Indian Hills did not pilot test any other technology prior to implementation.
Treatment System Parameters

- Design Capacity
  - 50 gpm maximum capacity
  - 25 gpm typical
  - 11-14 gpm actual

- Pretreatment/Post-treatment
  - 1 micron bag filters
  - Chlorination

- Treatment system footprint
  - Treatment system: 9.75' x 5.5'
  - Regeneration system: 13.3' x 6.5'
  - Residuals handling system:
    - 2,000 gal storage tank
  - Total system footprint: 20.5' x 9.75'
  - Building footprint: 30' x 50'

- Number of contactors
  - (2) – 3’ diameter; 6.75’ height

- Design Loading Rate
  - 7.27 gpm/ft^2 at design flow

- Bed volumes prior to regeneration
  - 125 BV

- Resin Type: MIEX DW 1401- Strong base anion exchange resin in chloride form

- Previous resins used: None

- Salt Consumption: 3,500 lbs/MG treated water

- Volume of brine generated
  - 2,800 gal brine/MG treated water
  - 99.7% water efficiency

- Monitoring:
  - Online nitrate analyzer
  - Laboratory samples
  - Field colorimeter

Residuals Management

The waste brine is sent to a 2,000 gallon underground storage tank. The brine is periodically pumped from the storage tank and ultimately land applied. Indian Hills is investigating deep well injection as an alternative disposal mechanism. The waste brine was analyzed in the pilot portion of the project and no unforeseen residuals were identified that would further limit the brine disposal options.

While not specifically analyzed at this site, waste brine from other MIEX® installations has not had detectable nitrosamine concentrations.

For the MIEX® System, Bed Volumes are defined as the volume of water treated per volume of resin regenerated. \( BV = \frac{\text{gal water treated}}{\text{gal resin regenerated}} \). For example, if 5 gal of resin were regenerated for every 1000 gal of water treated, the regeneration rate would be: \( BV = \frac{1000\text{gal}}{5\text{gal}} = 200\text{BV} \).

The design regeneration rate for the MIEX® System is 125 BV, meaning that 8.0 gal of resin are regenerated per 1000 gal of water treated. The system regeneration rate can be adjusted through the control system. There is approximately 1-2 gallons of resin attrition per 1 MG of treatment. Small amounts of resin are periodically added to the regeneration system manually.
Technology Benefits and Drawbacks

**Benefits**
- Consistent treatment performance
- Relatively low volumes of waste brine
- No nitrate dumping

**Drawbacks**
- Generation of waste brine
- Resin lost in the treatment must be removed prior to distribution

Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating and Monitoring Equipment:</td>
</tr>
<tr>
<td>(IX treatment system, including initial resin fill)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O&amp;M Costs (Total with explanation or component costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin:</td>
</tr>
<tr>
<td>Resin Disposal:</td>
</tr>
<tr>
<td>Brine Disposal or Treatment:</td>
</tr>
<tr>
<td>Chemicals:</td>
</tr>
</tbody>
</table>

Sources *:

Vaughan, Forrest, Orica Watercare, Personal Communication (August, 2010)
Martin, Barbara (September, 2010). Completed questionnaire.

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.
System Description

A California district operates 27 groundwater sources, 15 of which contain nitrate at or near the MCL. The district has considered and implemented a variety of solutions including IX, well modifications and well destruction. The nitrate impacted wells range in capacity from 500 gpm to 1000 gpm with nitrate ranging from 8 mg/L to 19 mg/L as N. It should be noted that a water quality goal of < 8 mg/L of nitrate as N has been implemented in the district, and all sources are treated to below this level.

The district began actively treating the nitrate contaminated sources in 2003 and the most recent system was installed in 2009. The district currently has 6 wells with active IX systems, 7 wells have been destructed or made inactive, 2 wells are being considered for well modifications and one well has an enhanced control system where there will be an automatic shut down if the nitrate levels exceed a predetermined level. The range of historical nitrate concentrations of the wells is shown below.

Source Water Quality

- Nitrate (mg/L N)
  - Well A- 2 – 13.1
  - Well B- 3 – 11
  - Well C- 1 – 11
  - Well D- 3 – 20
  - Well E- ND – 9.3
  - Well F- 3 – 12
  - Well G- 1 – 12
  - Well H- 2 – 16
  - Well I- 3 – 9
  - Well J- 1 – 8
  - Well K- 12
  - Well L- 20
  - Well M- 8
  - Well N- 8
  - Well O- 15

Treatment Technology Selection

The first nitrate treatment system the district installed was in 2003. At the time of installation IX was deemed the best available technology as it was the most economical with respect to the well’s nitrate concentrations and flow rates. When possible, the district elected to install similar systems on the wells that required treatment in an effort to establish operational parallels between their systems. When the footprint of the system or excessive nitrate concentrations made IX treatment infeasible, the district has elected for well destruction. In recent cases where treatment is necessary, the district has evaluated well modifications to determine if it is feasible to reduce the nitrate concentrations without the need for active treatment.
The following section shows the typical parameters of the districts individual IX systems with the exception of the salt consumption which represents the total salt use for the entire district.

**Treatment System Parameters**

- **Design Capacity**
  - 500-900 gpm
- **Pretreatment**
  - None
- **Treatment system foot print**
  - Two 35’ x 20’ cement slabs
  - Treatment system: 35’ x 10’
  - Housed in a cargo container
- **Residuals handling system:**
  - Three 12’ x 12’ dia. tanks
- **Ion exchange pressure vessels**
  - Number of vessels: 16
  - Diameter of vessels: 3’
  - Height of vessels: 6’
- **Design Loading Rate**
  - 12 gpm/ft²
- **Bed volumes prior to regeneration**
  - 300 BV
- **Treatment System Manufacturer:**
  - Envirogen Technologies
- **Resin Type:** Conventional type 1 ion exchange resin
- **Previous resins used:** None
- **Salt Consumption:** 25 tons/ week combined for all systems
- **Volume of brine generated:**
  - 1.3 bed volumes per vessel regenerated
  - Approximately 99.6% water efficiency
- **Monitoring:**
  - Online nitrate analyzer
  - Laboratory samples

**Residuals Management**

The waste brine is disposed of at an offsite facility. This decision has been impacted by elevated selenium and NDMA in the waste brine.

**Technology Benefits and Drawbacks**

**Benefits**
- Allows wells that would normally be offline due to nitrate contamination to be used for potable purposes
- The treatment system vendor provides on-site technical support and operations

**Drawbacks**
- Treatment system failure poses an acute health risk to the potable water system
- Time intensive operations if there is a treatment disruption
- The systems have numerous valves and moving parts. If there is a mechanical failure it can be difficult to identify the source
- High operating and brine disposal costs
- The district pays the system vendor for stand-by fees and service charges if the system is in stand-by mode during times of low water use
### Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total: $360,000 per unit – Electrical, Piping, Set-up, and Sampling/testing (construction costs)</td>
<td>The district does not own the treatment plants, tanks, resins, etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O&amp;M Costs (Total with explanation or component costs)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total: $59,239.41 per month, per unit</td>
<td></td>
</tr>
<tr>
<td>Brine Disposal or Treatment: $34,016.75 per month, per unit</td>
<td></td>
</tr>
<tr>
<td>Repair/Maintenance (not including Labor): $3,525.00 (service fee) per month, per unit</td>
<td></td>
</tr>
<tr>
<td>Salt: $13,541.41 (salt) per month, per unit</td>
<td></td>
</tr>
<tr>
<td>Other: $7,500.00 (stand by fee) per month, per unit</td>
<td>$656.25 (tax) per month, per unit</td>
</tr>
</tbody>
</table>
System Name: City of Chino
System Location: Chino, CA
PWSID: CA3610012
System Type: Community Water System

CASE #5

Treatment Type: Ion Exchange (IX)
Questionnaire completed by: Gilbert Aldaco, Water Utilities Supervisor, City of Chino Public Works
Startup Date: 2006

System Description

The City of Chino, CA operates 13 groundwater sources and 3 GWUDI (groundwater under direct influence of surface water) sources. All of the GWUDI and 8 of the groundwater sources are impacted by nitrate contamination. IX and blending are used to address high nitrate and perchlorate levels. One of the wells is inoperable due to perchlorate contamination. IX using the ISEP® system is used for the treatment of 3 wells ranging in capacity from 1100 to 2300 gpm and is being considered for a 4th well. Additionally, an Envirogen (formerly Basin Water) IX system is used for the treatment of an 800 gpm well. Treated surface water from the Metropolitan Water District of Southern California (MWDSC) and treated groundwater from the Chino Basin Desalter Authority is used for blending. The blend ratio is 3:1. The ISEP® system was built in 2005, with a capacity of 5000 gpm (7.2 MGD), and approved for operation in 2006.

Source Water Quality

- Nitrate (mg/L N) 9 – 45
- Co-contaminants
  - Perchlorate

Treatment Technology Selection

The costs and feasibility of several alternatives for nitrate treatment, including reverse osmosis, biological processes, and conventional (fixed bed) IX were investigated. Biological treatment and fixed bed IX were pilot-tested prior to installation of the current system. The ISEP® system was selected based in part on the potential to simultaneously address perchlorate contamination and due to the efficiency of operation.
Treatment System Parameters

- Design Capacity
  - 5000 gpm
- Pretreatment: Filtration
- Foot print
  - Treatment system: 4400 sq.ft.
  - Residuals handling: 2300 sq.ft.
  - Total system: 6700 sq.ft.
- Ion exchange vessels
  - Number of vessels: 30
  - Diameter of vessels: 3’
  - Height of vessels: 6’
- Max. nitrate concentration goal for delivered water:
  - ~ 8.2 mg/L as N
- Nitrate concentration goal for the treatment system (before blending):
  - ~ 4.3 mg/L as N
- Manufacturer: Calgon Carbon Corporation
- Resin Type: Purolite SBA

- Previous resins used: None
- Bed volumes prior to regeneration
  - Continuous regeneration
- Salt Consumption (@ 2400 gpm)
  - Nitrate mode – 4.9 tons/day
  - Perchlorate mode – 18.6 tons/day
- Volume of brine generated (@ 2400 gpm)
  - Nitrate mode: 12.7 gpm
    - 99.5% water efficiency
  - Perchlorate mode: 31 gpm
    - 98.7% water efficiency
- Monitoring:
  - Weekly effluent testing for nitrate and perchlorate
  - Monthly effluent testing for nitrite, sulfate and total Coliform
  - Monthly raw water testing for nitrate, perchlorate, nitrite, sulfate, total Coliform, HPC
- Grab Samples for resin byproduct testing were negative for nitrosamines.

Residuals Management

Waste brine is discharged to a non-reclaimable waste pipeline leading to the LA County Sanitation District, with a total disposal cost of ~$50,000/yr.

Technology Benefits and Drawbacks

Benefits
- Flexibility of operation and High efficiency
- Reliability and Ease of O & M

Drawbacks
- None listed

Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total:</strong> ~ $4.6 million</td>
</tr>
<tr>
<td><strong>Housing:</strong> ~ $492 K</td>
</tr>
<tr>
<td><strong>Piping:</strong> ~ $1.1 million</td>
</tr>
<tr>
<td><strong>Resin:</strong> ~ $350 K</td>
</tr>
<tr>
<td><strong>Testing:</strong> ~ $20 K</td>
</tr>
<tr>
<td><strong>Other:</strong> ~ $2.4 million for ISEP Equipment and Engineering; ~ $350 K for electrical upgrade; ~ $200 K for pumps and associated equipment.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual O&amp;M Costs (Total with explanation or component costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total:</strong> Not reported</td>
</tr>
<tr>
<td><strong>Brine Disposal or Treatment:</strong> ~ $50 K</td>
</tr>
<tr>
<td><strong>Chemicals:</strong> ~ $364 K for salt, ~ $50 K for hydrochloric acid</td>
</tr>
</tbody>
</table>
Additional Information

- Operators were not required to increase their level of certification to operate the treatment plant.
- When asked about the areas in which the nitrate treatment technology has exceeded expectations, the response was “Reliability and ability to effectively remove contaminants at varied flow rates (i.e., 1500 gpm to 5000 gpm).”
- There has been no incidence of a plant shutdown due to an alarm or exceedance of an MCL; however, the plant was shut down for approximately 1 month due to theft of computer control equipment.
3.2 Reverse Osmosis (RO)

Reverse osmosis can be a feasible option for nitrate removal in both municipal and Point-of-Use applications (Howe, 2004; Cevaal et al., 1995; and Black, 2003). The first commercial application of RO for potable water treatment was in Coalinga, CA in 1965 (National Academy of Engineering, 2008). RO can be used to address multiple contaminants simultaneously including ionic (i.e., nitrate, arsenic, sodium, chloride and fluoride), particulate (i.e., asbestos and Protozoan cysts) and organic constituents (i.e., some pesticides) (Dvorak & Skipton, 2008). Water is forced through a semi-permeable membrane under pressure such that the water passes through, while contaminants are impeded by the membrane. A typical process schematic of RO for nitrate removal from potable water is illustrated in Figure 3-7.

Figure 3-7 Reverse Osmosis Schematic.

The required pressure will be dependent on the concentration of solute in the feed water. The collected concentrate is high in nitrate and other rejected constituents (salts) and requires appropriate disposal. The extent to which the RO membrane removes constituents from the water is called the rejection rate. Rejection rates for sodium chloride and sodium nitrate can be as high as 98% and 93%, respectively (Elyanow & Persechino, 2005). The water recovery rate of an RO system refers to the “maximum percentage of permeate produced from a given feed flow,” and the flow/flux rate is “the maximum flow of permeate through a sq. ft. of the membrane” (Cevaal et al., 1995). Modifications and improvements to standard RO have led to the emergence of more efficient RO processes including High Efficiency Reverse Osmosis (HERO™) and Ultra-low Pressure Reverse Osmosis (ULPRO) systems.
### 3.2.1 Reverse Osmosis - Design Considerations

Table 3-6 summarizes key design considerations in the application of RO to nitrate removal from potable water.

#### Table 3-6 Summary of Design Considerations for Reverse Osmosis.

| RO Membranes | • Thin film membranes - Higher rejection rates, lower pressures than CTA membranes  
  • Cellulose triacetate membranes (CTA) - Not sensitive to chlorine  
  • Hollow fiber membranes - Compact configuration  
  • Ultra-low pressure RO membranes (ULPRO)  
  • Consider rejection rate, water recovery, and frequency of cleaning  
  • Multiple contaminant removal  |
|---------------------------------------------|
| Pretreatment | • Prevent membrane damage, scaling and biological, colloidal and organic fouling  
  • Scaling  
    o Acid (e.g., sulfuric acid) and/or anti-scaling agents (e.g., poly-acrylic acid)  
    o Water softening  
  • Biological fouling  
    o Upstream disinfection, but dechlorination to prevent membrane damage  
    ▪ Reducing agent (e.g., sodium bisulfate) or activated carbon  
  • Colloidal fouling  
    o Prefiltration to remove suspended solids  
    o Chemical treatment to keep suspended solids in solution  |
| Post-Treatment | • Avoid corrosion  
  o Adjust pH, restore alkalinity for buffering capacity (see remineralization) and/or add corrosion inhibitor (e.g., polyphosphate)  
  • Remineralization  
    o Blending, pH adjustment, addition of caustic soda, bicarbonate, sodium carbonate, phosphates, and/or silicates  
  • Blending, disinfection, and storage  |
| Chemical Usage | • pH adjustment, up and down (acids and bases)  
  • Anti-scalants  
  • Cleaning chemicals (acids and bases)  |
| O&M | • Frequency of membrane cleaning depends on water quality and membrane used  
  o Typically once a month for 1 hour  
  • Management of chemicals and prefiltration system  
  • Waste storage and disposal  
  • Membrane replacement/membrane life  
    o Up to 20 years or more with appropriate pretreatment and maintenance  
  • Monitoring of nitrate levels and membrane flux rate  
  • Automation can be feasible  
  • Low operational complexity (though higher than IX depending on pretreatment needs)  |
| System Components | • Maximize water recovery while minimizing energy use  
  o Pressure range of 100 to 200 psi  
  o Based on system size and feed water quality  
  • Key system configuration parameters are system flow rate, number of membranes/stages, system footprint, flux rate, water recovery rate, pump selection and sizing, pressure requirement, cleaning frequency  |
3.2.1.1 Water Quality

While regulated by operational pressure, the water recovery rate depends largely on feed composition. Problematic constituents include sulfate, calcite, calcium sulfate dehydrate (gypsum), silica, colloids, and microorganisms (Cevaal et al., 1995; Elyanow & Persechino, 2005; and Tarabara, 2007). Filtration upstream of the RO membranes is required to remove suspended solids. The life of the RO membranes and prefilters, and the frequency of membrane cleaning are also directly dependent on water quality and the efficiency of pretreatment measures.

Treatment efficiency can be compromised by membrane fouling. Anything that decreases available membrane surface area can limit the passage of water through the membrane and decrease water recovery. The four main types of membrane fouling are scaling, colloidal fouling, biological fouling and organic fouling. When the salt concentration in the feed water exceeds the saturation point at the membrane surface, precipitation of solids on the membrane can diminish the removal efficiency (Elyanow & Persechino, 2005). Scale forming constituents

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8 Pretreatment options to prevent scaling include addition of acid and/or anti-scaling agents and water softening. By decreasing the pH, the prevalent form of the carbonate cycle is bicarbonate rather than the carbonate ion. The precipitation of calcium carbonate will therefore be limited by the concentration of the carbonate ion. Note: the addition of acid helps only if the scale forming constituent is calcite, due to the speciation of carbonate (Lenntech, 2009c). Anti-scaling chemicals can function in three ways: threshold inhibition, crystal modification and dispersion (Lenntech, 2009c). Threshold inhibition occurs when the anti-scalant increases the solubility of a potential scalant to super saturation, allowing for a greater concentration to remain in solution. Crystal modification refers to the interference of negatively charged functional groups on the anti-scalant with salt crystal formation and membrane attachment. Anti-scaling chemicals can also promote dispersion of crystals by attaching to them and increasing their

---
such as calcium, barium and strontium salts pose a significant threat to RO by limiting the membrane surface area through which water can pass\(^9\). Development of biomass on the membrane surface can have a similar negative effect on performance\(^10\). Additionally, RO membranes have limited to zero tolerance for organic species, like grease and oil; organic fouling inhibits membrane performance (Lenntech, 2009e). Lastly, suspended solids not removed by pretreatment filtration can inhibit membrane performance through colloidal fouling\(^11\). Common pretreatment measures used to address membrane fouling are included in Table 3-6.

With acid addition in pretreatment, the permeate will need to be neutralized in post-treatment to avoid corrosion in the distribution system. Alternatively a corrosion inhibitor like polyphosphate or poly-orthophosphate can be used. Additionally, because RO is not selective in the removal of ions, treated water is demineralized. Thus, alkalinity may need to be added to restore minerals and buffering capacity to avoid corrosion in the distribution system\(^12\) (WHO, 2004 and Lenntech, 2009f). In post-treatment, blending (if used) follows the RO modules, after which water is disinfected and stored (Cevaal et al., 1995).

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\(^9\) The Langelier Saturation Index (LSI) and other corrosion indices are used to characterize the scaling potential of calcium carbonate (calcite), a commonly problematic constituent.

\(^10\) Upstream disinfection can limit membrane biofouling; however, additional measures must be taken to avoid membrane exposure to chlorine “by dosing with a reducing agent (such as sodium bisulfate) or by contacting with activated carbon” (Elyanow & Persechino, 2005).

\(^11\) The potential for colloidal fouling is typically characterized by the silt density index (SDI). A SDI greater than 3 can indicate the need for further pretreatment to minimize cleaning frequency and membrane damage (Lenntech, 2009e and Elyanow & Persechino, 2005). Chemical treatment can keep suspended solids in solution. Alternatively, a prefilter should be used to remove solids from the feed water (Remco Engineering).

\(^12\) It is important to note the relationship between alkalinity and pH. Alkalinity is a measure of buffering capacity or the resistance to changes in pH. Demineralized water or water with a low buffering capacity will be susceptible to more dramatic pH changes and is considered unstable. The pH of acidic product water should be adjusted and the buffering capacity of demineralized product water should be restored to avoid corrosion downstream. Options for the stabilization and remineralization of demineralized water include blending, pH adjustment, and addition of caustic soda, bicarbonate, sodium carbonate, phosphates, and/or silicates (WHO, 2004 and Lenntech, 2009f). Corrosion indices and models can be used to determine appropriate solutions for specific scenarios.
3.2.1.2 System Components and Site Considerations

RO systems are operated in stages. Following pretreatment, water is pumped through the membranes with booster pumps (Cevaal et al., 1995). Water recovery can be improved by passing the concentrate through the membranes more than once, but higher water recovery comes at the expense of increased scaling potential. As the water becomes more concentrated, saturation can lead to precipitation on the membrane (Elyanow & Persechino, 2005). The membrane flux rate can be decreased to limit scaling and increase membrane life (Cevaal et al., 1995). Key aspects of the system are pressure pumps, membrane configuration, membrane flux rate, number of stages/number of membranes, flow rate, and cleaning and anti-scalant requirements. Pump sizing is based on system size and the pressure requirements. The water recovery rate can be regulated by the operational pressure. The necessary pressure is dependent on the concentration of solute in the feed water. For example, with a conductivity of 1550 μS/cm, Panglish et al. (2005) determined the suitable pressure to be 145-174 psi. Similarly, at start-up, the operational pressure at an RO facility in Brighton, CO used for nitrate removal was 170 psi (Cevaal et al., 1995).

Two types of spiral wound RO membranes are commonly used: polyamide thin film composite membranes (TF) and cellulose triacetate membranes (CTA) (Remco Engineering and Cevaal et al., 1995). While TF membranes are capable of slightly higher rejection rates and can be operated at lower pressures, CTA membranes are not sensitive to chlorine (Remco Engineering). Hollow fiber RO membranes are also available, which can minimize system footprint but can be more susceptible to fouling from suspended solids (Hydranautics, 2001). Using recently developed ultra-low pressure RO (ULPRO) membranes, operational pressures can be reduced, decreasing power costs (Drewes et al., 2008). For additional information see the section Reverse Osmosis – Improvements and Modifications.

3.2.1.3 Residuals Management and Disposal

The volume of the waste stream can be considerable, ranging from 15% to 50% of the starting volume depending on the operational parameters (Howe, 2004). The waste stream, or concentrate, can be discharged to a wastewater treatment plant or a septic system (Bilidt, 1985).
and Howe, 2004), as long as the system can accommodate an increased salt concentration. Additional disposal options include drying beds, infiltration basins, trucking off-site, a coastal pipeline, deep well injection, advanced treatment, and most commonly, discharge to nearby surface salt-waters (i.e., oceans), when available (Howe, 2004). Important water quality characteristics of the waste brine (e.g., volume, salinity, metals and radionuclides) can affect the feasibility and costs of disposal. Options for inland communities are more limited and costly. Proximity to coastal power plants can be advantageous. Power plants using ocean water for cooling can provide a pre-existing infrastructure for disposal to ocean waters (Black, 2003).

The high cost of nitrate laden concentrate disposal has led to research into optimization of recycling and treatment of this waste stream. Coupling of RO systems with biological, chemical, or catalytic denitrification enables removal of nitrate from the waste concentrate, with reduction to nitrogen gas. Additionally, the Vibratory Shear Enhanced Process (VSEP), from New Logic Research, has been explored in the context of treatment of RO concentrate from wastewater treatment. By applying a shear force across the membrane, pore clogging by colloidal particles is minimized, leading to the potential for improved water recovery (Lozier et al., N.D.). Several combined configurations of interest are discussed below in a section devoted to Brine Treatment Alternatives and Hybrid Treatment Systems.

3.2.1.4 Maintenance, Monitoring and Operational Complexity

RO systems are typically highly automated, accommodating the greater operational complexity of RO operation, in comparison with IX. Several operational decisions will be dictated by operator availability and training. For instance, chemical addition in pretreatment can be quite effective, but will require more intensive maintenance. In contrast, opting for the more expensive choice, installing a water softener, will require less operator time. Membrane cleaning frequency varies widely and depends on the efficiency of pretreatment measures and water quality. Interruption of operation is not always necessary as the membranes can be isolated and cleaned in place (CIP) in stages. Membranes are typically cleaned with “acid or caustic solutions” (WA DOH, 2005). Cleaning agents are selected based on the cause of
membrane fouling. Cleaning and rinsing can take an hour and with effective pretreatment, monthly membrane cleaning should be sufficient (Remco Engineering and Bates, N.D.). With effective pretreatment, cleaning frequency can be significantly minimized. A RO plant in Milan, Italy using anti-scalants, requires cleaning only once every 18 months (Elyanow & Persechino, 2005). Filters should be checked weekly and, if used, the water softener should be maintained with sufficient salt every day. Effluent nitrate concentrations require monitoring to ensure compliance and to assess membrane performance. Over time, membrane degradation will lead to a gradual decrease in removal efficiency. Membrane life varies and can range from 5 to 20 years or more (Remco Engineering). Waste concentrate management consists of appropriate storage and disposal. More operationally complex than IX, operators of RO systems will typically require more training and system maintenance will demand more time and chemicals. However, with the implementation of appropriate pretreatment measures and the ability for system automation, operational complexity can be minimized.

### 3.2.2 Reverse Osmosis - Cost Considerations

For the efficient operation of an RO system, the fundamental objective is to maximize water recovery with the minimum amount of energy and chemical usage, while meeting necessary potable water guidelines. Factors affecting system cost include facility size (how much water), source water quality (including nitrate concentration), environmental factors (temperature and pH), and target effluent nitrate concentration (Bilidt, 1985). Lower operating pressures are less costly, but result in decreased water recovery. High operating pressures maximize water recovery (decreasing disposal costs), but increase energy demands and the need for “specialized pumps” (WA DOH, 2005). Thus, there is a trade-off between the costs of increasing water recovery (increased pretreatment and operational pressure) and the costs of disposal (pumping, storage and disposal expenses). In pretreatment, the use of anti-scalants rather than acid or a water softener is generally the least expensive. The use of a water softener is the least cost competitive option (Lenntech, 2009c). Regarding small water systems, “reverse osmosis is one of the most expensive forms of centralized treatment and will not likely be cost effective unless there are multiple contaminants needing removal” (WA DOH, 2005).
Capital costs for RO include land, housing, piping, storage tanks, O&M equipment, membranes, preliminary testing (pilot studies), permits, and training. O&M costs include membrane and filter replacement, membrane and filter disposal, concentrate disposal or treatment, chemical use (anti-scalant, pH adjustment, disinfection etc.), repair, maintenance, power, and labor.

Published cost information, from existing RO installations used for nitrate treatment, is listed in Table 3-7. Costs have been adjusted to 2010 dollars, unless indicated otherwise. Costs can be difficult to assess due to inconsistencies in how cost information is reported. Comparison of treatment costs is not always valid due to differences in influent water quality parameters, system size, waste management options, and system configuration. Published costs do not always include comparable information. It would be inappropriate to compare the O&M costs of a facility that excludes disposal costs with others that include this information. The listed cost information is provided as an approximate range of costs for specific facilities. Costs for implementing RO may be very different from those listed here. A thorough cost analysis of design parameters for specific locations would be required for accurate cost estimation. The information gathered through the questionnaire includes detailed costs associated with the unique case studies included in this analysis.

### Table 3-7 Selected Costs* of Reverse Osmosis Systems for Nitrate Removal.

<table>
<thead>
<tr>
<th>System Flow**</th>
<th>&lt; 0.5 MGD</th>
<th>0.5 – 5 MGD</th>
<th>5+ MGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annualized Capital Cost ($/1000 gal)</td>
<td>3.51 – 5.17 [1, 2]</td>
<td>1.00 – 1.30 [3, 4]</td>
<td>0.95 [3]</td>
</tr>
<tr>
<td>O&amp;M Cost ($/1000 gal)</td>
<td>1.46 – 16.16 [1, 2]</td>
<td>1.22 – 2.01 [3, 4]</td>
<td>1.63 [3]</td>
</tr>
<tr>
<td>Total Annualized Cost ($/1000 gal)</td>
<td>5.73 – 19.70 [1, 2]</td>
<td>2.52 – 3.21 [3, 4]</td>
<td>2.58 [3]</td>
</tr>
</tbody>
</table>

* Costs have been adjusted to 2010 dollars with 7% interest over 20 years, unless indicated otherwise.
** When available, costs are based on actual system flow rather than design capacity.

#### 3.2.3 Reverse Osmosis - Selected Research

Much research has focused on RO; Table A.2 of the Appendix is a list of recent studies relevant to nitrate removal from potable water and several examples of RO application. Current RO
research focuses on improvements of membranes and waste management, and decreasing energy use.

### 3.2.4 Reverse Osmosis - Summary of Advantages and Disadvantages

A summary of advantages and disadvantages of RO in comparison with other treatment options is listed in Table A.6 of the Appendix. Advantages of RO include high quality product water, multiple contaminant removal, desalination (TDS removal), feasible automation and application for POU applications. According to Elyanow & Persechino (2005) in their comparison of RO and EDR, “...the best economical choice for small capacity systems (<110 gpm or <25 m³/hr) are simple RO plants, which have less electrical and hydraulic complexity than EDR and other technologies.” In waters where salinity is a problem, RO can be better suited than IX due to the ability to remove multiple contaminants (including trihalomethane formation potential precursors (THMFPs)) (Cevaal et al., 1995).

Disadvantages of RO include high capital and O&M costs, membrane fouling susceptibility, high pretreatment and energy demands, and potentially large waste volume (lower water recovery) requiring disposal. The high cost of disposal from inland locations can result in RO treatment becoming cost prohibitive. Howe (2004) presents several alternatives to conventional disposal measures of RO waste brine, including reuse for industrial processes, processing (e.g., for salt production), or use in energy generation (“solar brine pond.”)

### 3.2.5 Reverse Osmosis - Improvements and Modifications

#### 3.2.5.1 Process Modification

High Efficiency Reverse Osmosis (HERO™) is a patented multi-step process enabling increased water recovery (greater than 90%) and minimizing cleaning requirements. This process limits scaling by incorporating hardness reduction, CO₂ stripping, and pH adjustment (GE, 2010b). Raw water is subjected to intensive pretreatment before passing through the RO membranes as follows (Engle, 2007):

- Weak acid cation exchange (WAC) is used to remove hardness ions,
- CO₂ stripping is used to remove carbonate and increase pH, and
- Base addition is used to increase the pH to a level of 10.5.
An example flow diagram is illustrated in Figure 3-8.

**Figure 3-8 Flow Chart of the HERO™ Process (Central Arizona Salinity Study, 2006).**

With such pretreatment, water fed to the RO membranes is softened and pH is adjusted high enough to significantly increase the solubility of silica. The high chemical usage and multiple steps result in a more complicated process than conventional RO. However, benefits include increased water recovery, decreased waste volume, and the ability to treat severely impaired and poor quality source water containing multiple contaminants (Engle, 2007).

The HERO™ process was initially designed to produce ultra-pure water for use in electronics applications and was patented by Debasish Mukhopadhyay with licensing rights for different applications (Engle, 2007). The HERO™ process has been implemented for drinking water treatment in the small community of Yalgoo, Australia to produce high quality drinking water.
from brackish groundwater high in silica and nitrate (Thomson et al., 2009; Water Corporation, 2007 and 2009). Higher removal rates result in decreased waste volume. Using the HERO™ process in Yalgoo, waste volumes are as low as “one-tenth of a conventional plant’s concentrated brine residue for disposal, eliminating the need for big evaporation ponds” (Water Corporation, 2007).

3.2.5.2 Membrane Modification – Low Pressure Membranes

Research and development in membrane technology has resulted in the emergence of Ultra-Low Pressure Reverse Osmosis (ULPRO). In contrast to the high pressures required for conventional RO, use of ULPRO membranes allows for lower operating pressures and improved flux rates. Energy demands can be reduced due to lower operating pressures; however, pretreatment practices to prevent membrane scaling and fouling are similar to those necessary for conventional RO membranes (Drewes et al. 2008). ULPRO membranes are available from several manufacturers. Operating pressures are in the range of 50 to 125 psi, while the pressures required for conventional RO membranes can be over 200 psi (Drewes et al., 2008; Excel Water, 2007; and Koch Membrane Systems, 2008). Drewes et al. (2008) compared the performance of ULPRO membranes and conventional RO membranes. Pretreatment included nano-filtration for both RO options. Findings indicate that the ULPRO membranes included in the study are capable of successfully removing nitrate and multiple additional contaminants to potable water standards. “With regard to operating costs, operating pressure is the only TMG [ULPRO membrane] operating parameter considered to deviate from the benchmark ESPA2 [conventional RO membrane] membrane. Pretreatment requirements and recovery rate are the same. Electrical consumption will be directly proportional to the required operating pressure” (Drewes et al., 2008, pg. 93). However, in the cost comparison between the two membranes, the benefits of lower operating pressures were overshadowed by the poor recovery of the ULPRO membranes after cleaning. The authors suggest that the cleaning of the ULPRO membranes would need to be optimized for an improved cost comparison.

3.2.6 Reverse Osmosis - Case Studies

The following case studies provide detailed information on the design and operation of full-scale RO treatment plants used for nitrate removal. Chino I Desalter and Chino II Desalter are combination systems using both RO and conventional IX.
System Description

A California water utility operates a system that has three groundwater supplies, one of which has nitrate at levels that exceed the MCL. The impacted well has nitrate concentrations that range from 17 mg/L to 19 mg/L as N and has a typical production capacity of 100 gpm. In 2002, the utility implemented a blending program and installed a RO system for nitrate control and treatment.

In RO, raw water is forced through a semi-permeable membrane under pressure such that the water passes through, while contaminants are impeded by the membrane. The required pressure will be dependent on the concentration of solute in the feed water. The collected concentrate is high in nitrate and other rejected constituents (salts) and requires appropriate disposal. The extent to which the RO membrane removes constituents from the water is called the rejection rate. Rejection rates for sodium chloride and sodium nitrate can be as high as 98% and 93%, respectively (Elyanow & Persechino, 2005).

The high nitrate supply is blended with one of the other two groundwater sources prior to RO treatment. The RO system reliably removes nitrate to below 8 mg/L as N and the water delivered to consumers typically has nitrate levels below 3 mg/L as N. This system utilizes a leach field type system to land apply the RO concentrate.

Source Water Quality

- Nitrate (mg/L N)
  - Average – 17
  - Minimum – 18
  - Maximum – 19

- Co-contaminants
  - Fluoride – 3.3 mg/L
  - Arsenic
  - Radium

Treatment Technology Selection

RO was selected as the most appropriate treatment system as the technology can reliably remove nitrate in addition to the co-occurring contaminants that are present, specifically fluoride, arsenic and radium.
## Treatment System Parameters

- **Design Capacity**
  - 120 gpm maximum capacity

- **Pretreatment**
  - Anti-scalant (Hyposperse MCD 150)

- **Treatment system foot print**
  - Treatment system: 15’ x 30’
  - Total system footprint: 40’ x 100’

- **RO System**
  - System manufacturer: Aria™
  - Membrane manufacturer: Osmronics
  - Number of stages: 4
  - Number of RO elements per stage: 4

- **Clean-in-place (CIP)**
  - CIP frequency: Quarterly (4x/year)
  - Initiated when there is a 15% decrease in permeate flow or salt rejection or a 15% increase in trans-membrane pressure
  - CIP chemicals: Dilute phosphoric acid

- **Water efficiency:** 80%

- **Monitoring**
  - Laboratory samples

- **Service life of membranes**
  - Approximately 8 years

## Residuals Management

The concentrate is disposed to an on-site leach field.

## Technology Benefits and Drawbacks

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effectively removes nitrate and other co-contaminants</td>
<td>Energy intensive</td>
</tr>
<tr>
<td>On-site concentrate disposal</td>
<td>Relatively low water efficiency (80%)</td>
</tr>
<tr>
<td>Consistent operations</td>
<td></td>
</tr>
</tbody>
</table>

## Treatment Technology Costs

Treatment technology costs are not available for this system.

## Operational Notes

The RO system has never had any extended unplanned shut downs or been shutdown as the result of an alarm. There has been an exceedance of the fluoride MCL that occurred near the end of the useful life of the membranes. The membranes have since been replaced, resolving this operational issue.

## References

System Description

The City of Brighton (City) utilizes six groundwater wells with production capacities ranging from 900 to 1500 gpm and one groundwater source which has been designated as groundwater under direct influence of surface water (GWUDI), as an emergency well, with a production capacity of 700 gpm. These seven sources are impacted by nitrate with average concentrations ranging from 10.6 mg/L to 20.4 mg/L of nitrate as N. The City has implemented RO with blending. The design capacity of the RO system is 6.65 MGD of permeate at 80% recovery (1150 gpm/train). Green sand and cartridge filters (Graver) are used to treat the GWUDI source, primarily for the removal of manganese. (Additional sources operated by the City that are not impacted by nitrate are purchased treated surface water and additional GWUDI wells.)

The original RO treatment system is illustrated below. Raw water enters the system with 40% of feed water bypassing the RO system and 60% of feed water passing to pretreatment. After anti-scalant addition, pretreated water is pressurized with boost pumps and passed to the RO skids. Waste concentrate exits the system for disposal and post-treatment of the permeate includes CO₂ stripping and the addition of chlorine and caustic. Post-treated water is blended with bypassed water and sent to storage and ultimately distribution.

Original RO Treatment Schematic (Cevaal et al., 1995).
Source Water Quality

- Nitrate (mg/L N)
  - Average – 10.6 to 20.4
  - Minimum – 4.52 to 15.8
  - Maximum – 17.8 to 25.5
- Co-contaminants
  - TDS: 580 to 1000 mg/L, RO TDS ~34 mg/L, Finished TDS ~280 mg/L
  - Fluoride: 1.3 mg/L
  - TOC: < 2 mg/L
  - Hardness: 370-480 mg/L as CaCO₃
  (historically, Cevaal et al., 1995)

Treatment Technology Selection

IX and EDR were also considered and pilot-tested prior to installation of the RO system. RO was selected due to nitrate levels and hardness. IX could have been less costly; however, the lower salt levels in RO concentrate make it possible to discharge waste to the South Platte River. “By selecting RO, the City hoped to actually reduce the salt load on the river with RO since many Brighton residents currently using home ion-exchange softening units would no longer use them” (Cevaal et al., 1995). Biological treatment is also being explored for the treatment of nitrate in the waste brine.
Treatment System Parameters

- **Design Capacity**
  - 6.65 MGD of permeate at 80% recovery (1150 gpm/train)

- **Pretreatment/Post-treatment**
  - Anti-scalant: King Lee Technologies Pre Treat Plus 0100 phosphonate
  - 5 micron cartridge filters
    - 2.5 inch diameter
    - 90 day replacement
  - pH adjustment
    - caustic soda (NaOH)
    - Air stripping (CO₂ removal)

- **Treatment system foot print**
  - Treatment system: 11,000 sq. ft. at installation (Cevaal et al., 1995)

- **Number of contactors**
  - 2 stages, 5 trains
  - RO elements/stage:
    - 36 x 18 array
    - 6 membranes/vessel
    - 324 total

- **Max. Concentration goal for delivered water**
  - 8 mg/L as N, (always produce lower)

- **Rejection Rate**
  - 95-98% rejection
  - Nitrate goal (before blending): ~1 mg/L as N

- **Flux rate of the RO membranes**
  - 13 gpd/sf

- **System Manufacturer**
  - Hydranautics and Hydrocode

- **Membrane Type**
  - CPA2 (no others used in past)

- **Membrane Life**
  - Unknown, none have required replacement (5 yrs. ago, the manufacturer said the membranes should last 3 more yrs.).

- **Membrane Cleaning**
  - Clean in Place initiated by time rather than decrease in flux. Every ~157 million gals treated (~2x/yr)
  - Chemicals: Nalco Product and Citric acid

- **Waste**
  - Discharge via Brine line to South Platte River
  - Recovery Rate: 80%

- **Monitoring**
  - Ion chromatography
    - At Source
    - At Point-of-Exit
  - Grab ISE (HACH)
    - At Blending Point
    - At Point-of-Exit
  - Testing once per year is required for compliance

Residuals Management

The waste concentrate is continuously discharged via a brine line to the South Platte River. Biological treatment is being explored for the treatment of the waste concentrate. The biological system would be located on the West side of the RO treatment system and would allow for reduction of nitrate in the waste stream. As mentioned above, the use of RO rather than ion exchange was an effort to decrease salt loading to the South Platte River. Historically, Brighton residents used in-home ion exchange units to soften water.

Technology Benefits and Drawbacks

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistent treatment performance</td>
<td>Constant generation of waste stream</td>
</tr>
<tr>
<td>Ease of operation</td>
<td>High power consumption</td>
</tr>
</tbody>
</table>
### Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating and Monitoring Equipment:</td>
</tr>
<tr>
<td>$8,253,000 (1993) 4MGD RO facility</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual O &amp; M Costs (Total with explanation or component costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total: $2,873,293.00</td>
</tr>
<tr>
<td>Membrane: 0</td>
</tr>
<tr>
<td>Membrane Disposal: 0</td>
</tr>
<tr>
<td>Brine Disposal or Treatment: 0</td>
</tr>
<tr>
<td>Chemicals: Approx. $100,000 year</td>
</tr>
<tr>
<td>Power: Approx $210,000 year for RO</td>
</tr>
<tr>
<td>Labor (Hours per Year): 10 hr/day, 7 day/wk</td>
</tr>
<tr>
<td>2 MGD Thornton treated: $3.60/1000 gallons</td>
</tr>
<tr>
<td>COMPLETE Cost (including treatment, distribution, everything):</td>
</tr>
<tr>
<td>$3.16/1000 gallons</td>
</tr>
</tbody>
</table>

### Additional Information:
- The level of certification required for plant operators is Colorado A treatment.
- During a power outage, there is a pause before the generators start. This required a manual restart of the system.
- This system has never produced water exceeding the nitrate MCL and has never had an unplanned shutdown exceeding one week.
- The major benefit of the RO system is the rejection rate allowing for removal of regulated contaminants.
- The most significant disadvantages are the high power consumption and the continuous brine discharge.
- The operator also noted that there has been a decreasing trend in nitrate levels in their sources.

### References


Anderson, D. (July 19, 2010). In-person interview and tour of the facility.

System Description

The Western Municipal Water District (District) operates a system comprised of seven wells, five of which contain nitrate above the MCL. Three of the nitrate impacted wells are treated by a 6.6 MGD RO facility. The permeate, or treated water, from the RO system is blended with the remaining two wells prior to distribution. The RO and blending facilities are collectively referred to as the Arlington Desalter. Approximately 60% of the total flow is treated by the RO system and the remaining 40% is blended with the treated water. The District targets a nitrate concentration of 5 mg/L as N in the distribution system.

The Arlington Desalter facilities were originally installed in 1990 to address the salt imbalance in the Upper Santa Ana Watershed. High salinity waters withdrawn from the South Arlington Basin were treated by the Arlington Desalter and subsequently discharged to the Santa Ana River for downstream use (and downstream drinking water treatment). The system was upgraded to a drinking water treatment facility in 2002 with the addition of disinfection, a clear well and a pump station used to pump drinking water into the distribution system for the city of Norco, CA.

Source Water Quality

- Nitrate (mg/L N)
  - Average – 17
  - Minimum – 10
  - Maximum – 20

- Co-contaminants
  - TDS – 1200 mg/L

Treatment Technology Selection

Due to the original intent of the system and the 2002 conversion for drinking water production, no other technologies were pilot tested prior to the installation of the RO and blending facilities. However, biological treatment of RO bypass water was recently pilot tested with full scale implementation anticipated. A case study about this fixed bed biological pilot study is listed separately.
## Treatment System Parameters

- **Design Capacity:** 6.6 MGD
- **Pretreatment/Post-treatment**
  - Anti-scalant: Y2K Anti-scalant
- **Treatment system footprint**
  - Treatment system: Approximately 7,500 ft$^2$ excluding clear well and pump station
- **Number Stages**
  - Stage 1-36 vessels each with 6 units
  - Stage 2-12 vessels each with 6 units
- **Max. Concentration goal for delivered water**
  - 5 mg/L as N
- **Water Recovery**
  - Original design: 75-76%
  - Current: 80%
- **Flux rate of the RO membranes**
  - 16 gpd/ft$^2$
- **System Manufacturer**
  - Hydranautics
- **Membrane Type**
  - Koch HR400
- **Membrane Life**
  - > 10 years
- **Membrane Cleaning**
  - Occurs 2 times per year
  - Chemicals: Low pH solution, hydrofluorosilic acid, high pH solution
- **Waste:** The RO concentrate is disposed of offshore via the Santa Ana Regional Interceptor (SARI) brine line
- **Monitoring**
  - Ion chromatography
  - Online nitrate analyzers

## Residuals Management

Waste is discharged to the Santa Ana Regional Interceptor (SARI) (Brine Line). The SARI line prevents degradation of natural waters caused by increased salinity. Managed by the Santa Ana Watershed Project Authority (SAWPA), the SARI line is a dedicated interceptor line built to help users meet discharge requirements. In addition to the Arlington Desalter, the SARI line is used by other dischargers including industrial and domestic sources. The District’s contribution to the total flow of the SARI line is approximately 5%. The SARI line carries water to the Orange County Sanitary District for wastewater treatment with ultimate offshore discharge.

Having access to the SARI line for brine disposal is a benefit of this system; however, there have been complications with the SARI line. Tremendous scaling problems in Arlington Desalter’s reach of the SARI line have resulted in the need to address calcium carbonate buildup and to consider additional cleanout points. Due to multiple discharge sources, the SARI line combines waters having very different water quality characteristics. Reactions within the mixed water can vary based on water chemistry. Several cleaning and maintenance options are being considered.

## Technology Benefits and Drawbacks

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable</td>
<td>Costly brine disposal</td>
</tr>
<tr>
<td>Access to SARI line for disposal</td>
<td>Complications with SARI line (scaling, etc.)</td>
</tr>
<tr>
<td>The treatment potential of the pre-existing RO system has been maximized through conversion for drinking water treatment</td>
<td></td>
</tr>
</tbody>
</table>
Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
<th>Unavailable for initial installation in 1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Capital Costs:</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>$2,931,228</td>
</tr>
<tr>
<td>Annual O&amp;M Costs (Total with explanation or component costs) (2009/2010)</td>
<td></td>
</tr>
<tr>
<td>Labor and Overhead:</td>
<td>$836,530</td>
</tr>
<tr>
<td>Outside Services:</td>
<td>$200,000</td>
</tr>
<tr>
<td>Emergency Repairs:</td>
<td>$25,000</td>
</tr>
<tr>
<td>General &amp; Administrative:</td>
<td>$85,000</td>
</tr>
<tr>
<td>Vehicle and Equipment:</td>
<td>$9,000</td>
</tr>
<tr>
<td>SARI Fixed Cost:</td>
<td>$151,800</td>
</tr>
<tr>
<td>Materials and Supplies:</td>
<td>$5,500</td>
</tr>
<tr>
<td>Permits and Fees:</td>
<td>$27,000</td>
</tr>
<tr>
<td>SARI Variable Cost:</td>
<td>$470,000</td>
</tr>
<tr>
<td>Chemicals:</td>
<td>$150,000</td>
</tr>
<tr>
<td>Energy:</td>
<td>$971,398</td>
</tr>
</tbody>
</table>

Additional Information

Regarding water recovery, the original design recovery rate was 75-76%. With modifications to anti-scalant use, the recovery rate increased to 78% and then to the current operational water recovery rate of 80%. To further improve the water recovery rate, additional testing is anticipated which will require engineering work and a cost-benefit analysis.

Currently used membranes are 10 years old and are still performing adequately with respect to operational parameters (flux rate, rejection rate, etc.). The District has budgeted for membrane replacement in this fiscal year; however, due to adequate performance, the current membranes may be used for an additional year. Membranes are actually attaining better water recovery than manufacturer specifications. Membrane life is also exceeding initial expectations.

Sources*

Bernosky, J. (November 5, 2010). Personal communication.
Bernosky, J. (October, 2010). Completed questionnaire.

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.
CASE #9
System Name: Chino Basin Desalter Authority (CDA) – Chino I Desalter
System Location: Chino, CA
PWSID: CA31610075
System Type: Community Water System

Startup Date: RO in 2000, IX added in 2005

System Description

The Chino Basin Desalter Authority (CDA) in southern California is a conglomerate of the following agencies: Inland Empire Utilities Agency (IEUA), Jurupa Community Services District (JCSD), City of Chino, City of Chino Hills, City of Ontario, City of Norco, Santa Ana River Water Company (SARWC), and Western Municipal Water District (WMWD). The CDA drinking water treatment facilities include two desalters: Chino I Desalter (discussed here) and the Chino II Desalter (discussed in the next case study) to address high TDS levels as well as nitrate contamination. The Chino I Desalter operates 14 source wells, 11 of which have raw nitrate levels well above the MCL. Treatment consists of a combination of RO, conventional anion exchange and blending. Sixty percent of total flow is treated with RO, 27% with IX and 13% passes only through VOC/Air-stripping prior to blending. The RO system was installed in 2000 and the IX system was added in 2005.

Source Water Quality

- Nitrate (mg/L N) (of nitrate impacted wells)
  - Average – ~32-65
  - Minimum – ~24-62
  - Maximum – ~35-76

- Co-contaminants
  - TDS: 1100 mg/L

Treatment Technology Selection

RO and IX were selected because combined they were determined to be the best mode of technology to adequately treat the high-TDS, high-nitrate source water. No other technologies were pilot-tested or considered prior to the installation of the system.
Treatment System Parameters

- **Design Capacity**
  - RO: 4940 gpm
  - IX: 3400 gpm

- **Pretreatment**
  - Anti-scalant: threshold inhibitor
  - Filtration: 1 micron pre-filters
  - pH adjustment: sulfuric acid

- **Post-treatment**
  - pH adjustment: sodium hydroxide

- **Treatment system foot print**
  - RO system: 143’ X 80’
  - IX system: 190’ X 60’

- **Number of contactors:**
  - 4 trains, 2 stages/train
  - RO elements/stage:
    - stage 1: 196 elements
    - stage 2: 98 elements

- **Ion exchange pressure vessels**
  - Number of vessels: 4
  - Diameter of vessels: 12’
  - Height of vessels: 11’

- **Design Loading Rate:** 1.66 gpm/ft²

- **Max. nitrate concentration goal for delivered water:** 7.75 mg/L as N

- **Nitrate concentration goal for the treatment system (before blending):** 2.15 mg/L as N

- **RO recovery rate:** 80%

- **RO membrane flux rate:** 0.9 gfd/psi

- **System Manufacturer:**
  - RO: Code-line
  - IX: Hungerford and Terry

- **Membrane Type:** Dow 400 BW-30

- **Membrane Life:** 5 years

- **Membrane Cleaning:**
  - Flux decrease initiates CIP
  - Every 6 month
  - Chemicals: for pH adjustment based on manufacturer recommendation

- **Resin Type:** Rohm and Hass Amberjet 4400 CL SBA

- **Volume treated prior to regeneration**
  - 700,000 gallons
  - Regeneration once every 12 hrs

- **Salt consumption:** 75 tons per week

- **Volume of brine/backwash:**
  - 53,000 gallons
  - 92.4 % water efficiency

- **Resin life:** Has not been replaced (online for 5 years)

- **Monitoring:**
  - Online nitrate analyzers
  - Treatment train
  - Blending point
  - POE
  - Laboratory samples
  - Quarterly testing for NDMA

Residuals Management

Concentrate/brine is discharged into a regional brine line called the Inland Empire Brine Line (IEBL) and formerly known as the Santa Ana Regional Interceptor (SARI).

Technology Benefits and Drawbacks

**Benefits**
- RO provides better removal
- IX is inexpensive
- IX has very low energy demands

**Drawbacks**
- RO is expensive
- High waste rate of RO
- IX does not address TDS
- Resin replacement will be costly
Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Based on projected costs in 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Plant Expansion Total (5000 afy expansion):</td>
</tr>
<tr>
<td>Ion Exchange Treatment (4.9 MGD):</td>
</tr>
<tr>
<td>Onsite Modifications</td>
</tr>
<tr>
<td>SARI Discharge Upgrades &amp; Storm Drain:</td>
</tr>
<tr>
<td>Additional SARI Capacity Purchase (not included in above total):</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O &amp; M Costs (Based on CDA 2010/11 Budget, for complete plant operation, not just the treatment system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total:</td>
</tr>
<tr>
<td>Chemicals:</td>
</tr>
<tr>
<td>Electricity – Plant Total:</td>
</tr>
<tr>
<td>Operating Fees:</td>
</tr>
<tr>
<td>Labor ($):</td>
</tr>
</tbody>
</table>

Additional Information

- The RO treatment system is described as falling short of expectations with respect to the high waste rate. 15% of all incoming water is sent to the brine line and delivered to a treatment plant outside of the local watershed at the Orange County Sanitation District.
- Plant shutdown has been required in the past due to high or low pressure, high nitrate and high TDS.
- In the event of insufficient treatment and the production of water in exceedance of an MCL, the plant has a MOV that closes automatically, sending water to a storm drain.

Sources*

Listed costs are based on:

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.
System Description

The Chino Basin Desalter Authority (CDA) in southern California is a conglomerate of the following agencies: Inland Empire Utilities Agency (IEUA), Jurupa Community Services District (JCSD), City of Chino, City of Chino Hills, City of Ontario, City of Norco, Santa Ana River Water Company (SARWC), and Western Municipal Water District (WMWD). The CDA drinking water treatment facilities include two desalters: Chino I Desalter (discussed above) and the Chino II Desalter (discussed here) to address high TDS levels as well as nitrate contamination. The Chino II Desalter operates 8 source wells, all of which have raw nitrate levels well above the MCL. Treatment consists of a combination of RO, conventional anion exchange and blending. The combined RO/IX system was installed in 2006.

Source Water Quality

- Nitrate (mg/L N) (of nitrate impacted wells)
  - Average – ~15-48
  - Minimum – ~11-41
  - Maximum – ~17-56

- Co-contaminants
  - TDS

Treatment Technology Selection

RO and IX were selected because combined they were determined to be the best mode of technology to adequately treat the high-TDS, high-nitrate source water. No other technologies were pilot-tested or considered prior to the installation of the system.
Treatment System Parameters

- **Design Capacity**
  - RO: 4167 gpm
  - IX: 2778 gpm

- **Pretreatment**
  - Anti-scalant: threshold inhibitor
  - Filtration: 1 micron pre-filters
  - pH adjustment: sulfuric acid

- **Post-treatment**
  - pH adjustment: sodium hydroxide

- **Treatment system footprint**
  - RO system: 30’ X 188’
  - IX system: 30’ X 188’
  - Total system: 60’ X 300’

- **Number of contactors:**
  - 3 trains
  - 48 vessels/train
  - RO elements/stage:
    - 7 elements per stage

- **Ion exchange pressure vessels**
  - Number of vessels: 4

- **Design Loading Rate:** 10.1 gpm/ft²

- **Max. nitrate concentration goal for delivered water:** 5.4 mg/L as N (goal), 7.54 mg/L as N(max.)

- **Nitrate concentration goal for the treatment system (before blending):** 0.86 mg/L as N

- **RO membrane flux rate:** 0.30 – 1.70 gfd/psi

- **System Manufacturer:**
  - RO: PROTEC Bekaert
  - IX: Hungerford and Terry

- **Membrane Type:** Dow/Filmtec Model BW30-400

- **Membrane Life:** ~5 years

- **Membrane Cleaning:**
  - Flux decrease initiates CIP
  - Every 6 months to 1X per year
  - Chemicals: King Lee (anti-scalant), high/low pH, Silica Cleaner

- **Resin Type:** Rohm and Hass Amberjet 4400 CL SBA

- **Volume treated prior to regeneration**
  - 0.8-1.4 MGD
  - Regeneration is based on nitrate levels

- **Salt consumption:** 50 tons per week

- **Volume of brine/backwash:** NA

- **Resin life:** NA

- **Monitoring:**
  - Online nitrate analyzers
    - At source
    - Blending point
    - POE
  - Laboratory samples

Residuals Management

Concentrate/brine is discharged to an industrial sewer that drains to the Inland Empire Brine Line (IEBL). Waste is transported 45 miles to the Orange County Sanitation District.

Technology Benefits and Drawbacks

**Benefits**
- RO works well for nitrate removal
- IX is less expensive

**Drawbacks**
- RO is expensive
- IX does not accomplish contaminant removal as well as RO
Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Based on projected costs in 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Plant Total (10400 AFY):</td>
</tr>
<tr>
<td>Ion Exchange Treatment:</td>
</tr>
<tr>
<td>Chino II Desalter:</td>
</tr>
<tr>
<td>RO Membranes:</td>
</tr>
<tr>
<td>Ion Exchange Land (not included in above total):</td>
</tr>
<tr>
<td>Ion Exchange SARI Fee (not included in above total):</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O &amp; M Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total:</td>
</tr>
<tr>
<td>Chemicals:</td>
</tr>
<tr>
<td>Electricity – Plant Total:</td>
</tr>
<tr>
<td>Operating Fees:</td>
</tr>
<tr>
<td>Labor ($)</td>
</tr>
</tbody>
</table>

Additional Information

- Operator certification levels range from T-3 to T-5.
- Plant shutdown has been required in the past due to chemical pump failure and high clearwell.
- Overall the combined system is described as working well but at a high price.

Sources*

Listed costs are based on:

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.
3.3 Electrodialysis (ED/EDR/SED)

Competitive with RO, the use of Electrodialysis (ED) including electrodialysis reversal (EDR) and selective electrodialysis (SED) in potable water treatment (Figure 3-9) has increased in recent years, offering the potential for improved water recovery, the ability to selectively remove nitrate ions, and the minimization of chemical and energy requirements (Kneifel & Luhrs, 1988; Banasiak & Schafer, 2009; Hell et al., 1998; Koparal & Ogutveren, 2002; Midaoui et al., 2002; Sahli et al., 2008; and Kapoor & Viraraghavan, 1997).

Figure 3-9 Electrodialysis Reversal Schematic.

Nitrate removal is accomplished by passing an electrical current through a series or stack of anion and cation exchange membranes, resulting in the movement of ions from the feed solution to a concentrated waste stream. Illustrated in Figure 3-10, nitrate ions (and other anions) move through the anion exchange membrane toward the anode. Continuing toward the anode, nitrate is rejected by the anion-impermeable cation exchange membrane and trapped in the recycled waste stream. Cations can be removed in a similar manner, migrating toward the cathode through the cation exchange membrane and rejected by the cation-impermeable anion exchange membrane. Nitrate selective membranes allow for treatment without significantly altering the balance of other ions in the water.
The electrical current is passed through the system with the migration of ions across the membranes. For every anion that leaves a compartment, a cation of equivalent charge also leaves, maintaining the charge balance in each compartment. Across the system, the flow of electrons, moving from the cathode to the anode (negative to positive), is governed by the movement of ions through the membrane stack and by the reactions in the electrode compartment. Small levels of gaseous by-products must be removed. Electrolysis of water generates oxygen at the anode and hydrogen gas at the cathode and chloride can be reduced at the anode, producing chlorine gas (AWWA, 1995). The electrode compartment is rinsed to restore ions for current transfer and to remove unwanted reaction products.

Requiring constant electrical current and low-pressure water, ED has inherent energy demands. However, voltage adjustment enables selective demineralization. “Plants can be designed to remove from 50 to 99 percent of source water contaminants or dissolved solids. Source water
salinities of less than 100 mg/L up to 12,000 mg/L TDS can be successfully treated to produce finished water of less than 10 mg/L” (AWWA, 1995).

A detailed case study of an EDR plant in Spain is included in section 3.3.6.

3.3.1 Electrodialysis - Design Considerations

Table 3-8, summarizes key design considerations in the application of ED to nitrate removal from potable water.
| Membranes                                                                 | • Use of anion and cation exchange membranes |
|                                                                         | • Selective membranes                        |
|                                                                         |   o Monovalent versus multivalent             |
|                                                                         | • Consider water recovery and frequency of cleaning |
| Pretreatment                                                            | • Lower pretreatment requirements because this is not direct filtration |
|                                                                         | • EDR systems can avoid or limit chemical use |
|                                                                         | • Prevention of scaling and fouling           |
|                                                                         |   o Filtration to remove suspended solids     |
|                                                                         |   o Treatment for iron and manganese removal  |
|                                                                         |   o Water softening or use of anti-scalants or acid to prevent scaling |
| Post-Treatment                                                          | • pH adjustment to avoid corrosion (if acid used to prevent scaling) |
|                                                                         | • Disinfection                               |
| Chemical Usage                                                          | • Possible pH adjustment (acids and bases)    |
|                                                                         | • Possible anti-scalants                      |
|                                                                         | • Possible cleaning chemicals                 |
| O&M                                                                     | • Highly automated                           |
|                                                                         | • Frequency of membrane cleaning depends on water quality and membrane used |
|                                                                         |   o Polarity reversal (electrodialysis reversal) multiple times per hour |
|                                                                         |   minimizes fouling                           |
|                                                                         | o ED systems can require weekly cleaning      |
|                                                                         | • Management of chemicals and prefiltration system |
|                                                                         |   o Including electrode compartment rinse solution |
|                                                                         | • Waste storage and disposal                  |
|                                                                         | • High monitoring demands                     |
|                                                                         | • Potentially higher operator demand than IX and RO, due to system complexity |
| System Components                                                       | • Maximize water recovery while minimizing energy use |
|                                                                         | • Key aspects of the system are pretreatment requirements, the number and configuration of electrodialysis stacks and stages, membrane selection and configuration, operating voltage and pressure, reversal frequency (for EDR), gas venting of the anode and cathode compartments, disinfection, “brine loop, electrode rinse loop, concentrate discharge, and dosing station” (Hell et al., 1998). |
| Waste Management and Disposal                                           | • Concentrate disposal of greatest concern for inland systems |
|                                                                         |   o Close proximity to coastal waters is beneficial for brine/concentrate disposal |
|                                                                         | • Management options include sewer or septic system, reuse for irrigation, drying beds, trucking off-site, coastal pipeline, deep well injection and advanced treatment |
|                                                                         | • Disposal options can be limited by waste brine/concentrate water quality (e.g., volume, salinity, metals and radionuclides) |
|                                                                         | • Optimization of recycling and treatment of waste concentrate |
| Limitations                                                             | • Need to prevent membrane scaling and fouling |
|                                                                         |   o Hardness, iron, manganese and suspended solids |
|                                                                         | • Disposal of waste concentrate               |
|                                                                         | • High system complexity                       |

### 3.3.1.1 Water Quality

Membrane life, cleaning frequency, and pretreatment needs are dependent on feed water quality. Pretreatment may be needed for iron levels above 0.3 mg/L, manganese levels above 0.1 mg/L, and hydrogen sulfide levels exceeding 0.3 mg/L (WA DOH, 2005). Specifications for
an example EDR system from GE indicate feed water turbidity levels should be < 0.5 NTU with
typical TDS levels between 100 and 3,000 mg/L (maximum 12,000 mg/L) (GE, 2008). SDI limits
are generally higher for EDR than for RO, with typical limits of 12 and 4-5, respectively (Elyanow
& Pereschino, 2005). Softening may be necessary to reduce hardness, while prefiltration
diminishes suspended solids. The potential for scaling increases with increasing TDS and is
exacerbated by increased solids precipitation with higher water recovery goals. To minimize
fouling/scaling, membranes can be treated with anti-scaling chemicals and cleaned with acid
(AWWA, 1995). However, in comparison with other membrane processes, fouling is minimal
because the membrane is subjected to the transfer of ions (directed by the electrical current),
rather than the transfer of the entire feed stream. Unfortunately, because ED does not serve as
a filter (the water does not pass through the membrane), ED fails to remove microbial
contamination (AWWA, 1995). Prefiltration in pretreatment and disinfection in post-treatment
address these concerns.

To further minimize fouling and thus the need for chemical addition, the polarity of the system
can be reversed with electrodialysis reversal (EDR). By reversing the polarity (and the solution
flow direction) several times per hour, ions move in the opposite direction through the
membranes, minimizing buildup and the need for chemical addition to control scaling.
Biological fouling concerns are lower than other separation processes due to development of
membranes that are “more organic resistant and chlorine tolerant” (Elyanow & Persechino,
2005). ED depends on the transfer of an electrical current and is therefore more efficient when
used for brackish waters. In low conductivity feed waters, the ion removal efficiency declines.
In contrast to conventional RO, EDR is unaffected by silica.

3.3.1.2 System Components and Site Considerations
ED and EDR systems are operated in stages. Water recovery can be improved with stages
operated in series while capacity can be increased with stages operated in parallel. Key aspects
of the system are pretreatment requirements, the number and configuration of electrodialysis
stacks and stages, membrane selection and configuration, operating voltage (based on desired
removal), reversal frequency (for EDR), gas venting of the anode and cathode compartments,
disinfection, “brine loop, electrode rinse loop, concentrate discharge, and dosing station” (Hell et al., 1998).

The membranes used in ED/EDR are anion and cation exchange membranes. Membranes have been designed for selective removal based on valency (monovalent versus multivalent) to screen for particular constituents (AWWA, 1995). Alternating different selective membranes in the membrane stages can avoid precipitation in the concentrate stream. For example, one stage can remove calcium and a second stage can remove sulfate (to an alternate concentrate stream), this prevents calcium sulfate precipitation (AWWA, 1995).

3.3.1.3 Residuals Management and Disposal
Waste management requirements are similar to RO and IX; however, the burden of disposal in ED/EDR systems is not as significant due to higher water recovery, selective removal, and the lack of direct filtration (Reahl, 2006). Disposal options include sewer, septic system, drying beds, off-site trucking, coastal pipeline, deep well injection, reuse for irrigation, and advanced treatment. Important water quality characteristics of the concentrate (e.g., volume, salinity, metals and radionuclides) can affect the feasibility and costs of disposal options. Several combined configurations of interest are discussed below in a section devoted to Brine Treatment Alternatives and Hybrid Treatment Systems.

3.3.1.4 Maintenance, Monitoring and Operational Complexity
Although ED/EDR systems are amenable to automation, operator demands can be higher than other separation processes as “daily monitoring of differential pressure and other operational parameters should be performed” (WA DOH, 2005, pg. 30). While ED systems have greater pretreatment demands and can require membrane cleaning once a week, EDR systems minimize pretreatment demands and scaling issues, but can still have higher maintenance demands than RO, due to the complexity of the system (Kapoor & Viraraghavan, 1997). Appropriate gas venting is important to avoid hazardous conditions (WA DOH, 2005). Membrane life will depend on water quality and pretreatment measures. However, due to the lack of direct filtration and operation under low pressure, membranes are long lasting, and do not require frequent replacement.
3.3.2 Electrodialysis - Cost Considerations

For the efficient operation of an ED system, the fundamental objective is to maximize water recovery with the minimum amount of energy and chemical usage, while meeting necessary potable water guidelines. Factors affecting system cost include facility size, source water quality (including nitrate concentration and other contaminants), target effluent nitrate concentration, and disposal options.

Capital costs for ED/EDR systems include land, housing, piping, storage tanks, O&M equipment, cation and anion exchange membranes, preliminary testing (pilot studies), permits, and training. O&M costs include membrane replacement, membrane disposal, concentrate disposal or treatment, chemical use (limited – anti-scalant etc.), repair, maintenance, power, and labor.

Very little published cost information from existing ED systems used for nitrate removal is available in the literature, due to the limited number of full-scale systems. Costs have been adjusted to 2010 dollars, unless indicated otherwise. Costs of ED systems are most comparable to RO. However, in some instances, ED can be the less costly choice due to the greater pretreatment and post-treatment demands (higher chemical use and post-treatment pH adjustment) of RO (Reahl, 2006). EDR can be chosen over RO when high water recovery is a priority, especially if land must be purchased for concentrate ponds. “New technology has also reduced the capital and operating cost of EDR nitrate removal by increasing the hydraulic efficiency of the EDR stacks and pumping system” (Elyanow & Persechino, 2005). In a technical paper from GE Water & Process Technologies (the primary supplier of EDR systems in the U.S.), Werner & Gottberg (2005) compared O&M costs of an electrodialysis plant in Suffolk, VA (not specifically for nitrate treatment) and a conventional surface water treatment plant (Table 3-9). Based on O&M costs, the electrodialysis plant was cost competitive with the conventional surface water treatment plant (Werner & Gottberg, 2005). It is unclear how disposal costs were included in this study. High water recovery in comparison with other removal processes and disposal of waste concentrate to a nearby estuarine tributary would maintain low disposal costs (Werner & Gottberg, 2005). According to Ameridia, the American division of Eurodia Industrie (a manufacturer of EDR systems), the capital investment for a nitrate treatment EDR unit for a ~0.5 MGD system (in 2005) was $475,000 or $0.94 per gallon of daily capacity.
($559,653 or $1.11 in 2010 dollars, respectively) (Ameridia). However, additional capital costs are likely not included in this figure.

Table 3-9 Comparison of EDR and Conventional Surface Water Treatment O&M Costs (from Werner & Gottberg, 2005).

<table>
<thead>
<tr>
<th>O&amp;M Category</th>
<th>EDR (/1000 gallons)</th>
<th>Conventional (/1000 gallons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed</td>
<td>$0.72 ($1.07 adjusted)</td>
<td>$0.72 ($1.07 adjusted)</td>
</tr>
<tr>
<td>Professional</td>
<td>$0.06 ($0.09 adjusted)</td>
<td>$0.05 ($0.07 adjusted)</td>
</tr>
<tr>
<td>Services</td>
<td>$0.02 ($0.03 adjusted)</td>
<td>$0.13 ($0.19 adjusted)</td>
</tr>
<tr>
<td>Chemicals</td>
<td>$0.21 ($0.31 adjusted)</td>
<td>$0.25 ($0.37 adjusted)</td>
</tr>
<tr>
<td>Utilities</td>
<td>$0.17 ($0.25 adjusted)</td>
<td>$0.17 ($0.25 adjusted)</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$0.23 ($0.34 adjusted)</td>
<td>$0.00</td>
</tr>
<tr>
<td>Membrane</td>
<td>$0.19 ($0.34 adjusted)</td>
<td>$0.00</td>
</tr>
<tr>
<td>Replacement</td>
<td>$0.17 ($0.25 adjusted)</td>
<td>$0.17 ($0.25 adjusted)</td>
</tr>
<tr>
<td>Production (1997)</td>
<td>827,339,440 gallons</td>
<td>390,953,560 gallons</td>
</tr>
<tr>
<td>Total O&amp;M Cost</td>
<td>$1.41 ($2.09 adjusted)</td>
<td>$1.32 ($1.96 adjusted)</td>
</tr>
</tbody>
</table>

Costs adjusted from 1998 dollars to 2010 dollars.

The listed cost information is provided as an approximate range of costs for specific facilities. Costs for implementing ED may be very different from those listed here. A thorough cost analysis of design parameters for specific locations would be required for accurate cost estimation.

3.3.3 Electrodialysis - Selected Research

Much research on ED has focused on desalination applications. Table A.3 of the Appendix is a list of recent studies relevant to nitrate removal from potable water and several examples of ED application. Research is focused on the influence of co-contaminants on system performance and improvements in exchange membranes, including nitrate selectivity.

3.3.4 Electrodialysis - Summary of Advantages and Disadvantages

A summary of advantages and disadvantages of ED in comparison with other treatment options is listed in Table A.6 of the Appendix. Advantages of ED/EDR systems include limited to no chemical usage, long lasting membranes (infrequent replacement), selective removal of target species, flexibility in removal rate through voltage control, better water recovery (lower waste volume), feasible automation, and multiple contaminant removal (Hell et al., 1998; AWWA, 1995; WA DOH, 2005; and Prato & Parent, 1993). With the ability to selectively remove multiple contaminants, ED/EDR systems can be used to address the following constituents: TDS,
total chromium, chromium-6, arsenic, perchlorate, sodium, mercury, chloride, copper, sulfate, uranium, fluoride, nitrate/nitrite, iron, selenium, hardness, barium, bicarbonate, cadmium and strontium (AWWA, 1995 and GE, 2010). Using current reversal, EDR offers additional advantages, improving system performance by “detaching polarization films, breaking up freshly precipitated scale or seeds of scale before they can cause damage, reducing slime formations on membrane surfaces, reducing problems associated with the use of chemicals, and cleaning electrodes with acid automatically during anodic operation” (AWWA, 1995). Additionally, in comparison with RO systems, EDR can treat waters with higher SDI, silica and chlorine levels (Elyanow & Persechino, 2005).

Disadvantages of ED/EDR systems include the possible need for pretreatment to prevent membrane scaling and fouling, waste disposal, high maintenance demands, costs (comparable to RO systems), the need to vent gaseous by-products, the potential for precipitation (especially for high water recovery), high system complexity, and limited manufacturers with U.S. experience (e.g., GE is the primary source of EDR systems for drinking water in the U.S.). Additionally, unlike RO, ED does not remove uncharged constituents in the water.

### 3.3.5 Modifications to Electrodialysis

#### 3.3.5.1 Selective Electrodialysis (SED)

Since 1997, selective electrodialysis (SED) has been successfully implemented, providing high quality potable water throughout Israel and reducing national water costs by 55%. Developed by Shikun & Binui, formerly Nitron, Ltd., SED offers high water recovery (up to 95%), thereby minimizing waste volume (Nitron, 2010). The SED system is accepted by the EPA as a nitrate treatment option for large plants (Nitron, 2009). While similar to traditional ED processes, SED utilizes nitrate selective membranes which have been shown to increase operational performance when used for nitrate treatment.

The nitrate selective membranes used in the SED process have been shown to remove up to 70% of nitrate from solution. At the same time, sulfate ions and carbonate ions, which have a tendency to cause scaling issues in the concentrate stream of traditional ED/EDR and RO technologies, are more readily rejected by the nitrate selective membranes used in the SED process.
process. As a result, the scaling potential is reduced in the concentrate stream. Since scaling problems are minimized, membrane cleaning frequency, maintenance costs, and down time are reduced compared to traditional EDR installations. Another important aspect of membrane selectivity is the energy efficiency of the process. Energy efficiency is related to the extent of ion transfer in ED/EDR and SED technologies. In traditional ED/EDR energy use is less focused, resulting in the removal of many ions, including ions that do not need to be addressed. SED specifically targets nitrate ions, avoiding energy use for the removal of non-target ions and improving energy efficiency.

Pretreatment can be limited to filtration, energy efficiency is maximized due to low pressure operation (2-4 bars), chemical use is limited to concentrate treatment, and low maintenance demands are possible due to automation, remote monitoring and control, and infrequent cleaning. In the SED process there is no change in the pH of the product water. This avoids the need for pH adjustment or remineralization in post-treatment (Nitron, 2009, 2010). Membranes are cleaned in place (CIP) for 1 hour every 4-6 months and membrane life is typically 7-10 years (Nitron, 2010). Additional advantages of SED include constant membrane performance, no chemical contact with potable water, the simplicity of the system consisting of pre-filtration and membrane stacks (UV can be added for disinfection), and a small footprint (Nitron, 2009b). Potential drawbacks of SED include the lack of full-scale application in the U.S. for nitrate removal from drinking water and, unlike RO, ED does not remove uncharged constituents in the water.

_A detailed case study of the use of SED for nitrate removal at locations in Israel is included in the following section._

### 3.3.6 Electrodialysis - Case Studies

The following case studies provide detailed information on the design and operation of full-scale EDR and SED treatment plants used for nitrate removal.
System Name: Gandia EDR  
System Location: Valencia, Spain  
System Type: NA

CASE #11

Treatment Type: Electrodialysis Reversal (EDR)  
Questionnaire completed by: GE Water & Process Technologies  
Startup Date: 2007

System Description

Gandia is a tourist area on the Mediterranean coast of Spain. The area sees peak demand during the summer months when the population almost triples. Spanish Legislature released royal Decree 140/2003 which changed the nitrate limit to 50 mg/L as nitrate (11.3 mg/L as N). This new law required treatment of the existing system to achieve the new nitrate limits. Additionally, the existing well systems had deteriorated over time, forcing the municipality to find alternate wells to feed the community.

Upon analysis of the wells (old and new), it was determined that the nitrate levels were too high to meet the drinking water standard. The well samples had up to 80 mg/L as nitrate (18.1 mg/L as N). Treatment was necessary to produce acceptable levels of nitrate in the product water. An evaluation was conducted and EDR was selected as the technology of choice for the Gandia treatment plants. EDR offered high recovery while effectively reducing the nitrate levels below 25 mg/L as nitrate (5.6 mg/L as N).

EDR was piloted on the wells to verify the nitrate removals and operating cost estimates for power requirements and chemical consumption. The pilot study was successful, and the final systems were designed around 90% water recovery with the overall nitrate removal of 73%.

Source Water Quality

- Nitrate (mg/L N)  
  - $< 80$ mg/L as NO$_3$
Treatment Technology Selection

EDR, Selective ED, and Reverse Osmosis were considered for treating the Gandia Wells. EDR was eventually selected for the high recovery and reduced operating costs compared to RO. SED was ruled out based on the high capital costs of the system.

Treatment System Parameters

- **Design Capacity**
  - 3,260 gpm
- **EDR System**
  - No. of modules: 4
  - Lines per module: 5
  - Stages per line: 2
- **Water recovery rate:**
  - 94.3%

Water Quality Results

The table below summarizes the water quality of the raw water, finished water, concentrate stream, and the total waste from the Gandia EDR facility. Total waste includes concentrate blowdown, electrode waste, and off-spec product from the system.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Raw Water</th>
<th>Treated Water</th>
<th>Percent Removal</th>
<th>Concentrate Stream</th>
<th>Total Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>82</td>
<td>24.9</td>
<td>70%</td>
<td>772.6</td>
<td>544.3</td>
</tr>
<tr>
<td>Mg</td>
<td>24</td>
<td>8.3</td>
<td>65%</td>
<td>213.7</td>
<td>151.0</td>
</tr>
<tr>
<td>Na</td>
<td>23</td>
<td>10</td>
<td>57%</td>
<td>180</td>
<td>128.1</td>
</tr>
<tr>
<td>K</td>
<td>1.0</td>
<td>0.3</td>
<td>70%</td>
<td>9.2</td>
<td>6.5</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>250</td>
<td>99.1</td>
<td>60%</td>
<td>2074.1</td>
<td>1471.2</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>58</td>
<td>12.7</td>
<td>78%</td>
<td>605.2</td>
<td>424.4</td>
</tr>
<tr>
<td>Cl</td>
<td>29</td>
<td>7.5</td>
<td>74%</td>
<td>289.3</td>
<td>203.3</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>60</td>
<td>16.6</td>
<td>72%</td>
<td>584.4</td>
<td>411.1</td>
</tr>
<tr>
<td>TDS</td>
<td>527</td>
<td>179.3</td>
<td>66%</td>
<td>4728.6</td>
<td>3339.8</td>
</tr>
<tr>
<td>pH</td>
<td>7.5</td>
<td>7.1</td>
<td></td>
<td>8.3</td>
<td>8.1</td>
</tr>
</tbody>
</table>
Technology Benefits and Drawbacks

**Benefits**

- EDR membranes are chlorine tolerant, providing means to control biological growth.
- Relatively low operational expenditures
  Membrane life expectancy is 15 years.
  Low chemical consumption compared to other technologies.
  Lower energy consumption compared to RO.
- High water recovery, small concentrate stream for disposal compared to other technologies.

**Drawbacks**

- Higher capital cost than RO
- System footprint larger than competitive technologies

Operating Costs

Capital costs for the EDR system were not provided.

<table>
<thead>
<tr>
<th>O &amp; M Costs (Total with explanation or component costs)</th>
<th>Unit</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor:</td>
<td>$/1,000 gal</td>
<td>0.17</td>
</tr>
<tr>
<td>Energy:</td>
<td>$/1,000 gal</td>
<td>0.15</td>
</tr>
<tr>
<td>Maintenance:</td>
<td>$/1,000 gal</td>
<td>0.03</td>
</tr>
<tr>
<td>Chemicals:</td>
<td>$/1,000 gal</td>
<td>0.10</td>
</tr>
<tr>
<td>Consumables:</td>
<td>$/1,000 gal</td>
<td>0.19</td>
</tr>
<tr>
<td>Overhead:</td>
<td>$/1,000 gal</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>$/1,000 gal</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Operational Notes

Operating costs were based on estimates prior to plant start-up. After four years of operating, the plant has not replaced any membranes.

In 2010, another facility (L'Eliana) was commissioned in the Valencia area for 2.9 MGD production rate for nitrate removal using the EDR technology.

**Sources**

“Nitrate and Hardness Removal with Electrodialysis Reversal (EDR) in Gandia, (Valencia, Spain)” by Vicent Sarrió Cháfer, Javier Sanchis Carbonell, Juan Carlos de Armas Torrent

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.*
System Name: Weizmann Institute
System Location: Rechovot, Israel
System Type: NA

CASE #12

Treatment Type: Selective Electrodialysis (SED)
Questionnaire completed by: Shikun & Binui Environmental Group
Startup Date: 2008

System Description

The Weizmann Institute of Science (Institute), located in Rechovot, Israel, is one of the top-ranking multidisciplinary research institutions in the world. In 2007, the nitrate MCL in the Israeli National drinking water regulations changed from 90 mg/L (20.3 mg/L as N) to 70 mg/L (15.8 mg/L as N). Because of that change, two of the Institute's wells were removed from the drinking water supply and the Institute had to rely on external water suppliers. Over time, municipal and national water costs increased. The Institute’s management looked for solutions to solve nitrate problems and enable them to reopen the Institute's wells.

Prior to treatment the wells were used for potable purposes and the Institute’s irrigation needs. Selective Electrodialysis (SED) was identified as the Institute’s most appropriate treatment technology. A SED system was implemented for the 310 gpm well. The Institute opted for treatment of one well and uses the second well as a dedicated irrigation supply source. The nitrate enriched concentrate from the SED process is fed into the non-potable irrigation system where the nitrate enhances plant growth.

SED has been successfully implemented, throughout Israel since 2007. Developed by Nitron, Ltd., SED offers high water recovery (up to 95%), thereby minimizing waste volume. Pretreatment can generally be limited to filtration, energy efficiency is maximized due to low pressure operation (30-60 psi), chemical use is limited to concentrate treatment (no need for chemical addition to feed or product water), and low maintenance demands are possible due to automation, remote monitoring and control and infrequent cleaning. Membranes are cleaned in place (CIP) for 1 hour every 4-6 months and membrane life is typically 7-10 years.

Source Water Quality

- Nitrate (mg/L N)
  - Average – 19
  - Minimum – 19
  - Maximum – 20

Treatment Technology Selection

SED and RO were considered for treating the Weizmann Institute Well. A 10 year life cycle cost analysis that included capital and operations costs identified SED as the more cost effective solution.

<table>
<thead>
<tr>
<th>Treatment Type</th>
<th>Selective Electrodialysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Capacity</td>
<td>310 gpm</td>
</tr>
<tr>
<td>Raw Water Nitrate</td>
<td>19 – 20 mg/L</td>
</tr>
</tbody>
</table>
Treatment System Parameters

- Design Capacity
  - 310 gpm
- Pretreatment
  - Cartridge filtration
- Post-treatment
  - Chlorination
  - Acid addition (pH 4.5 - 5) to concentrate to prevent the precipitation of calcium carbonate and calcium sulfate in the concentrate cells
- Treatment system foot print
  - Treatment system: 8’ x 5’
  - Building footprint: Butler building - 50’ x 13’ as per client request
- Bed volumes prior to regeneration
  - 345-470 BV (approximately 220,000-300,000 gallons treated)
- Water recovery rate:
  - 94.3%
- SED unit information:
  - Number of SED units: 1
  - Membrane pairs: 240
  - 59% Nitrate reduction
  - 30% TDS reduction
  - Energy consumption: 2.3 KWh/1,000 gal
- Monitoring:
  - Online nitrate analyzer
  - Laboratory nitrate samples
  - Online pH meters
  - Online turbidity
  - Online conductivity meters

Water Quality Results

The table below summarizes the water quality of the raw water, finished water, and concentrate stream from the Weizmann Institute.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Raw Water</th>
<th>Treated Water</th>
<th>Percent Removal</th>
<th>Concentrate Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>194</td>
<td>105</td>
<td>45.9%</td>
<td>2051</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>95</td>
<td>92</td>
<td>3.0%</td>
<td>140</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>232</td>
<td>165</td>
<td>28.7%</td>
<td>442</td>
</tr>
<tr>
<td>NO₃</td>
<td>92</td>
<td>44</td>
<td>52.2%</td>
<td>835</td>
</tr>
<tr>
<td>Na</td>
<td>109</td>
<td>76</td>
<td>30.4%</td>
<td>627</td>
</tr>
<tr>
<td>Ca</td>
<td>118</td>
<td>73</td>
<td>37.8%</td>
<td>808</td>
</tr>
<tr>
<td>Mg</td>
<td>24</td>
<td>15</td>
<td>36.6%</td>
<td>160</td>
</tr>
<tr>
<td>K</td>
<td>3.6</td>
<td>2.5</td>
<td>30.6%</td>
<td>20.5</td>
</tr>
<tr>
<td>Ba</td>
<td>0.149</td>
<td>0.093</td>
<td>37.8%</td>
<td>1.020</td>
</tr>
<tr>
<td>Sr</td>
<td>0.84</td>
<td>0.52</td>
<td>37.8%</td>
<td>5.75</td>
</tr>
<tr>
<td>TDS</td>
<td>869</td>
<td>574</td>
<td>33.9%</td>
<td>5090</td>
</tr>
<tr>
<td>pH</td>
<td>7.8</td>
<td>7.8</td>
<td></td>
<td>6.5</td>
</tr>
</tbody>
</table>

Residuals Management

The concentrate from the SED process is fed into the Weizmann Institutes non-potable system which is used for irrigation purposes. Since the SED process selectively removes nitrate, the Total Dissolved Solids (TDS) of the concentrate is less than a RO system would be if it were treating the same water, which allows the concentrate to be used for irrigation without the salinity adversely affecting plant growth. This management approach is also beneficial since the concentrated nitrate solution has limited the amount of fertilizer applied by the Weizmann Institute.
Technology Benefits and Drawbacks

**Benefits**
- Ease of regeneration
- Fewer chemicals than comparable technologies
- Membranes 7-10 years life span
- Energy consumption less than that of RO
- High water recovery
- Concentrate solution has relatively low TDS which may increase disposal options

**Drawbacks**
- Capital intensive technology
- Requires specific operator training

Treatment Technology Costs

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
<th>$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total:</td>
<td>650,000</td>
<td></td>
</tr>
<tr>
<td>Housing: Light building 50X13 feet. According to customer demands.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piping: Pipes, electric valves, storage tanks (the largest would be with a volume of about 180 cu. ft. for product water)</td>
<td>50,000</td>
<td></td>
</tr>
<tr>
<td>Storage Tanks (include description of uses):</td>
<td></td>
<td>See above.</td>
</tr>
<tr>
<td>Operating and Monitoring Equipment: Control system, remote assistance for the control system, on line nitrate measurement, conductivity, pH, turbidity.</td>
<td>90,000</td>
<td></td>
</tr>
<tr>
<td>Membranes Modules: Complete SED membrane stack.</td>
<td>300,000</td>
<td></td>
</tr>
<tr>
<td>Permits: According to local regulations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (Please describe): Design, Electricity boards – design and manufacturing &amp; erection, Pumps and blowers.</td>
<td>210,000</td>
<td></td>
</tr>
</tbody>
</table>
Operational Notes

The SED system is highly instrumented and the PLC has over 200 monitored inputs. As a result there have not been any failures that have resulted in water in violation of the MCL delivered to consumers. While there have been failures resulting in alarms and shutdowns, the control system has been robust enough to shut down the system and prevent water with high nitrate entering the distribution system. Typical shutdowns can be rectified in a matter of hours and normal operation is resumed.

Sources*:
Merhav, Neta. (October, 2010). Completed questionnaire.

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.
3.4 Biological Denitrification (BD)

Commonly used in wastewater treatment, biological reactors are emerging as a method for denitrification of potable water with the potential to address multiple contaminants including nitrate, chromate, perchlorate, and trace organic chemicals (Brown, 2008). Biological denitrification (BD) in potable water treatment has been implemented in Europe since 1804 (Lenntech, 2009), with recent full-scale systems in France, Germany, Austria, Poland, Italy and Great Britain (Meyer, N.D. and Dördelmann, 2009). To date, full-scale drinking water applications in the United States have been limited to a single plant in Coyle, OK (no longer online). However, two full-scale biological denitrification systems are anticipated in California within the next couple of years.

Denitrification occurs naturally in the environment as part of nitrogen cycling. Application of biological denitrification to potable water treatment (Figure 3-11) utilizes denitrifying bacteria to reduce nitrate to innocuous nitrogen gas in the absence of oxygen (anoxic conditions).

Figure 3-11 Biological Denitrification Schematic.

The reduction of nitrate proceeds stepwise in accordance with Eqn. 9. In contrast with the separation processes of IX, RO and ED/EDR, nitrate is reduced and thereby removed from the system rather than simply being displaced to a concentrated waste stream.

\[
\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2
\]  

(Eqn. 9)

Denitrifying bacteria require an electron donor (substrate) for the reduction of nitrate to nitrogen gas. In conventional wastewater treatment, substrate addition is not typically needed, because the wastewater contains sufficient carbon for denitrification to occur. However,
depending on the source, substrate addition is often required for the biological denitrification of potable water. The addition of a carbon substrate in potable water treatment is somewhat counter intuitive. In fact, one principal objective of potable water treatment is to minimize dissolved carbon in the water to minimize growth of microbes (e.g., biofilms) and production of disinfectant byproducts (e.g., THMs). Feed water composition may need to be further augmented with the addition of nutrients required for cell growth (phosphorus for example). Autotrophic bacteria utilize sulfur or hydrogen as an electron donor and inorganic carbon (typically carbon dioxide) as a carbon source for cell growth (Eqns. 10 and 11), while heterotrophic bacteria consume an organic carbon substrate, like methanol, ethanol or acetate (Eqn. 12) (Kapoor & Viraraghavan, 1997, Mateju et al., 1992).

\[
\begin{align*}
\text{Eqn. 10} & : 11\text{S}^0 + 0.5\text{CO}_2 + 10\text{NO}_3^- + 2.54\text{H}_2\text{O} + 1.71\text{NH}_4^+ \rightarrow 0.92\text{C}_5\text{H}_7\text{O}_2\text{N} + 11\text{SO}_4^{2-} + 5.4\text{N}_2 + 9.62\text{H}^+ \\
\text{Eqn. 11} & : \text{H}_2 + 0.35\text{NO}_3^- + 0.35\text{H}^+ + 0.052\text{CO}_2 \rightarrow 0.010\text{C}_5\text{H}_7\text{O}_2\text{N} + 0.17\text{N}_2 + 1.1\text{H}_2\text{O} \\
\text{Eqn. 12} & : 1.08\text{CH}_3\text{OH} + \text{NO}_3^- + \text{H}^+ \rightarrow 0.065\text{C}_5\text{H}_7\text{O}_2\text{N} + 0.467\text{N}_2 + 0.76\text{CO}_2 + 2.44\text{H}_2\text{O}
\end{align*}
\]

Eqns. 10 through 12 illustrate the overall denitrification reaction defining the stoichiometric relationship between electron donor, carbon source and nitrate in the production of cells and the conversion of nitrate to nitrogen gas. Not all nitrogen is converted to nitrogen gas. Some nitrogen is required for cell growth. The governing stoichiometric equation indicates the necessary dose and varies with the substrate used. For example, the stoichiometric factor for acetic acid is 0.82 moles of acetic acid per mole of nitrate (Dördelmann et al., 2006).

Various species of bacteria are responsible for denitrification including \textit{Thiobacillus denitrificans}, \textit{Micrococcus denitrificans}, \textit{Pseudomonas maltophilia} and \textit{Pseudomonas putrefaciens} (Kapoor & Viraraghavan, 1997). Due to slower bacterial growth rates, autotrophic denitrification offers the advantage of minimizing biomass accumulation; however, autotrophic denitrification requires alkalinity to supply the inorganic carbon source (carbon dioxide) for cell growth (Della Rocca et al., 2006). BIODEN® and DENICARB® are heterotrophic biological denitrification processes, while DENITROPUR® is an autotrophic option. Selected full scale biological denitrification systems are listed in Table 3-10 (Dördelmann, 2009).
Table 3-10  Full Scale Biological Denitrification Systems for Potable Water Treatment.

<table>
<thead>
<tr>
<th>Location</th>
<th>Reactor Configuration</th>
<th>Substrate, Denitrification type</th>
<th>Flow rate m³/h (MGD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neuss [1]</td>
<td>Fixed bed, downflow</td>
<td>Acetic acid, Heterotrophic</td>
<td>150 (0.95)</td>
</tr>
<tr>
<td>Frankfurt Airport [1]</td>
<td>Fluidized bed, upflow, DENICARB®</td>
<td>Ethanol, Heterotrophic</td>
<td>320 (2.03)</td>
</tr>
<tr>
<td>Aschaffenburg [1]</td>
<td>Fixed bed, upflow, DENITROPUR®</td>
<td>Hydrogen and CO₂, Autotrophic</td>
<td>1600 (10.14)</td>
</tr>
<tr>
<td>Föhr Island [1]</td>
<td></td>
<td></td>
<td>90 (0.57)</td>
</tr>
<tr>
<td>Austria</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obersiebenbrunn [1]</td>
<td>Fixed bed, downflow, BIODEN®</td>
<td>Ethanol, Heterotrophic</td>
<td>180 (1.14)</td>
</tr>
<tr>
<td>Poland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Czestochowa [1]</td>
<td>Fixed bed, downflow, BIODEN®</td>
<td>Ethanol, Heterotrophic</td>
<td>500 (3.17)</td>
</tr>
<tr>
<td>1: Dördelmann, 2009</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In their review of potable water treatment methods for the removal of nitrate, Mateju et al. (1992), Kapoor & Viraraghavan (1997), Soares (2000) and Shrimali & Singh (2001) discuss previous research and applications of biological denitrification. Problems associated with the application of conventional biological denitrification to potable water treatment include additional post-treatment for removal of biomass and dissolved organics, increased capital costs, and sensitivity to environmental conditions (Kapoor & Viraraghavan, 1997). To address these concerns, several treatment configurations using biological denitrification have been developed.

3.4.1 Biological Denitrification – Design Considerations

Table 3-11 summarizes key design considerations in the application of biological denitrification for nitrate removal from potable water.
### Table 3-11 Summary of Design Considerations for Biological Denitrification.

| Pretreatment | • Substrate and nutrient dosing  
|             | • pH adjustment |
| Post-Treatment | • Carbon adsorption for organic carbon removal  
|               | o Carbon adsorption is not always required  
|               | o Residual substrate removal can be accomplished via biological filtration  
|               | • Aeration  
|               | • Filtration  
|               | • Disinfection |
| Chemical Usage | • Possible pH adjustment  
|                | • Substrate and nutrient addition  
|                | • Coagulant/polymer use to meet turbidity standards  
|                | • Disinfection |
| O&M | • Historically operator intensive  
|     | o Operator demands can be minimized with the latest design configurations  
|     | • Constant monitoring required to assure efficient removal, health of microbes etc.  
|     | • Monitoring of nitrite and ammonia will also be necessary due to the potential for incomplete denitrification  
|     | • Management of chemicals  
|     | • Waste sludge storage and disposal  
|     | • New plants can be highly automated  
|     | • Historically viewed as operationally complex  
|     | o More unit processes than IX  
|     | o New design configurations can minimize complexity (e.g., fixed bed reactor) |
| System Components | Important process considerations include (Dördelmann, 2009):  
|                  | • Dosage requirements of substrate and nutrients  
|                  | • Reactor configuration and governing equation of the biological process  
|                  | • Aeration to remove nitrogen gas and provide oxygen  
|                  | • Filtration to remove particulate matter  
|                  | • Activated carbon may be used to remove substrate residual and avoid DBP formation (for heterotrophic systems)  
|                  | • Disinfection |
| Waste Management and Disposal | • Sludge disposal – Biological solids and residual organic matter  
|                          | • No waste brine or concentrate as in separation processes |
| Limitations | • Requires anoxic conditions  
|             | • Chemical management  
|             | • Few examples for nitrate removal in the U.S.  
|             | • Post-treatment requirements  
|             | • Operator training  
|             | • Intermittent use of wells may be challenging due to the need for acclimation of microorganisms |

#### 3.4.1.1 Water Quality

Anoxic conditions are required for denitrification to occur. In the presence of oxygen (> 0.1 mg/L) bacteria preferentially reduce oxygen rather than nitrate, diminishing the efficiency of the process. For all configurations, the optimal growth of microbes must be considered.
Control and monitoring of water quality characteristics including temperature, pH, salinity, and oxidation reduction potential (ORP) can be fundamental to the stability and efficiency of the biological denitrification system (WA DOH, 2005). For biological denitrification, near neutral pH is preferred (7-8) and temperatures below 5°C/41°F can inhibit denitrification (WA DOH, 2005).

Pretreatment will include addition of substrate and nutrients in the appropriate dose while post-treatment requirements can include coagulant addition, filtration, gas exchange, and disinfection for the removal of biomass, particulates and substrate residuals (Dördelmann et al., 2006 and Panglisch et al., 2005).

3.4.1.2 System Components and Site Considerations

Important process considerations in the design and operation of BD systems include (Dördelmann, 2009):

- Dosage requirements of substrate and nutrients
- Reactor configuration and governing equation of the biological process
- Aeration to remove nitrogen gas and provide oxygen
- Filtration to remove particulate matter
- Activated carbon to remove substrate residual and avoid DBP formation (for heterotrophic)
- Disinfection

Conditions should be optimized to ensure complete denitrification. In addition to nitrate reduction to meet the nitrate MCL (10 mg/L as N), effluent nitrite levels must not exceed the nitrite MCL of 1 mg/L as N.

System configurations of biological denitrification include: fluidized bed reactor, fixed bed reactor, membrane biofilm reactor, and bio-electrochemical reactors. In situ options (including bank filtration) have also been explored in the research.

3.4.1.3 Fixed Bed

Fixed bed biological reactors can be in up-flow or down-flow systems in a pressurized or open flow configuration (Brown, 2008). Typical options for growth support media are “sand, plastic, or granular activated carbon” (Brown, 2008). Accumulation of biomass in the media leads to
head loss requiring periodic backwashing. Post-treatment requirements can include filtration, 
gas exchange, and disinfection for the removal of biomass, particulates and substrate residuals 
(Dördelmann et al., 2006 and Panglisch et al., 2005). The fixed bed configuration “is often 
coupled with pre-ozonation to improve the removal of organic material, which reduces 
regrowth potential and DBP formation in distribution systems” (Brown, 2008). (See 
Dördelmann et al. (2006), Panglisch et al. (2005), Soares (2002), Upadhyaya (2010), Meyer et al. 
(2010), City of Thornton (2010), Carollo Engineers (2008) and Aslan (2005) in Table A.4 for 
research examples of the fixed bed configuration.)

_A detailed case study of the Fixed Bed configuration of biological denitrification in Riverside, CA is included in section 3.4.5._

### 3.4.1.4 Fluidized Bed

The fluidized bed reactor operates in an up-flow mode, resulting in granular growth support 
media expansion. Fluidizing the granular media offers several advantages over the fixed bed 
configuration. Flow resistance is minimized and the system does not need to be taken off line 
for backwashing because accumulated biomass is removed by the fast flowing feed water 
and/or “in-line mechanical shearing devices” (Brown, 2008). “The biofilm is detached from the 
support material only upon strong mechanical effect, thus the excess biomass can be 
intermittently removed from the reactor, independently of the purified water” (Holló & Czakó, 
1987).

Maintenance of the sufficient up-flow velocity can be achieved through recycled flow and 
reactor volumes are designed for a typical bed expansion of 25 to 30% (Brown, 2008). (See 
Webster & Togna (2009), Kurt et al. (1987) and Holló & Czakó (1987) in Table A.4 for research 
examples of the fluidized bed configuration.)

_A detailed case study of the Fluidized Bed configuration of biological denitrification in Rialto, CA is included in section 3.4.5._

### 3.4.1.5 Membrane Biological Reactor (MBR)/Membrane Biofilm Reactor (MBfR)

With the addition of membrane technology to conventional biological denitrification, common 
concerns of biological treatment can be minimized through physical separation of biomass and
substrate from the treated water. In a comprehensive review of membrane bioreactors, McAdam & Judd (2006) present the pros and cons of a variety of MBR configurations (Table 3-12). MBRs can be designed for autotrophic or heterotrophic denitrification. Pressurized systems have been explored using submerged ultrafiltration membranes or external (sidestream) MBRs, while pressure neutral diffusion systems have been implemented with ion exchange membranes and microporous membranes (Brown, 2008 and McAdam & Judd, 2006). Membrane types include hollow fiber, ion exchange, microporous and flat sheet. (See Meyer et al. (2010), City of Thornton (2010), Mansell & Schroeder (2002), Ergas & Rheinheimer (2004), Chung et al. (2007), and Nerenberg & Rittman (2004) in Table A.4 for research examples of MBR configurations.)

Applied Process Technology, Inc. (APT) has developed an autotrophic membrane biofilm reactor (MBfR) (Gormly & Borg, APT) using hydrogen gas as the electron donor rather than a carbon substrate. As part of a long term pilot scale study13 in Glendale, AZ, APT’s MBfR was examined to address high nitrate levels in groundwater. This autotrophic biological denitrification system successfully reduced nitrate levels to below the MCL. Three types of hollow fiber membranes were examined for substrate delivery. Operational concerns highlighted by this study include (Meyer et al., 2010):

- Problems with leaking fibers,
- Hydrogen sulfide formation due to excessive hydrogen gas pressure,
- Ammonium generation from biomass decay due to operational interruption and insufficient electron donor, and
- Nitrite levels above the 1 mg/L nitrite as N limit (incomplete denitrification).

To address these concerns, the authors suggest:

- The use of the latest optimized membranes,
- Consistent and adequate nutrient and electron donor supply,
- Oxidation of nitrite in post-treatment if necessary,
- Stable loading and continuous operation to avoid system upset, and

---

• Parallel reactors to allow for maintenance and repair.

The MBfR pilot was one of three biological configurations examined in Glendale. Two upflow heterotrophic fixed bed bioreactors were also examined, each with a different media type. Post-treatment included filtration using biologically active carbon and ozonation. The two most promising biological treatment options, the MBfR and the upflow fixed bed bioreactor with plastic media, were compared with each other and also with an IX system. Overall, using a multi-criteria analysis with consideration of sustainability, the MBfR scored the most favorably regarding benefits, but the least favorably regarding life cycle costs. The life cycle costs of both the IX and the fixed bed bioreactor options were lower than that of the MBfR. The Glendale study highlights several key areas of future research including “a shut-down test where biological treatment processes sit dry for a period of time and then re-start at optimal hydraulic loading rates [and] a re-acclimation test where systems are re-initiated after losing all viable biomass” (Meyer et al., 2010).

As a promising technology, with further research and design optimization to reduce costs, the MBfR may become a more feasible treatment option. As of 2008, a demonstration project of the MBfR for nitrate and Dibromochloropropane (DBCP) removal was under consideration for the City of Fresno, CA to test performance of the MBfR as an alternative treatment option (City of Fresno, 2008).

Table 3-12 Membrane Biological Reactor Configurations.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusive Extraction</td>
<td>Relying on diffusion for nitrate transfer through the membrane, extractive MBRs (aka Fixed MBRs) do not directly filter the treatment stream, but they do provide separation of the denitrification chamber (substrate, biomass and associated residuals) and the treatment stream. Key issues are the transfer of biomass or substrate across membrane, the potential for fouling/scaling, and the need for a high transfer rate of nitrate to the denitrification compartment.</td>
</tr>
<tr>
<td>Microporous Membranes</td>
<td></td>
</tr>
<tr>
<td>Diffusive Extraction</td>
<td>With the use of an ion exchange membrane rather than a microporous membrane, selectivity for nitrate and decreased mass transfer from the denitrification compartment are facilitated; however, capital and maintenance costs of ion exchange membranes can be significant and the need to manage membrane fouling persists (McAdam &amp; Judd, 2006).</td>
</tr>
<tr>
<td>Ion Exchange Membranes</td>
<td></td>
</tr>
<tr>
<td>Gaseous Substrate Delivery</td>
<td>In autotrophic systems, membranes can be used for gaseous substrate delivery, (i.e., hydrogen gas) (McAdam &amp; Judd, 2006). Previous problems with limited hydrogen gas transfer have been addressed with the use of hollow fiber membranes for delivery. Substrate passes through the membrane to the biofilm on the outer membrane surface. The membrane does not separate the biomass from the treatment stream and “the membrane is not used for direct filtration” (McAdam &amp; Judd, 2006); the presence of “sloughed biomass” and biological residuals in the treatment</td>
</tr>
<tr>
<td>Hollow Fiber Membranes</td>
<td></td>
</tr>
</tbody>
</table>
Pressure Driven Direct Filtration MBRs

Pressurized MBRs provide the advantage of direct filtration. Pressure is used to draw the denitrified water through the submerged membrane, leaving behind biomass and other undesirable constituents. However, the use of this configuration for denitrification is complicated by the fact that aeration is typically used for mixing and to minimize fouling of the external membrane surface (Brown, 2008).

3.4.1.6 In Situ Denitrification

Bank filtration refers to the withdrawal of surface water through an embankment. The porous media (soil) of the bank serves as a biological reactor providing treatment through “filtration, dilution, sorption, and biodegradation processes” (Brown, 2008). Bank filtration was employed in water treatment as early as 1870 along the Rhine River in Germany (Brown, 2008). As a recent example, a full scale study in Aurora, CO demonstrated effective nitrate removal with bank filtration of surface water from the South Platte River (Waskom, Carlson & Brauer, N.D.). Biological denitrification for in situ removal of nitrate from groundwater was explored by Hunter (2001), Haugen et al. (2002) and Schnobrich et al. (2007). Through in situ denitrification, the subsurface acts as the porous media through which water is filtered. Residual organics and biomass from denitrifiers can thus be removed naturally. (See Hunter (2001), Haugen et al. (2002), and Schnobrich et al. (2007) in Table A.4 for research examples of in situ application.)

3.4.1.7 Post-Treatment Requirements - Filtration/Taste & Odor/Disinfection

With the use of microorganisms and the addition of a carbon substrate, post-treatment is essential to meet turbidity standards, to remove biomass and residual organic matter, and to address taste and odor concerns. Post-treatment must include disinfection to address biological contamination and can also include dual media filtration and/or activated carbon filtration and aeration (individual state regulations will need to address local requirements).

3.4.1.8 Residuals Management and Disposal

In contrast to the concentrated waste stream from removal processes, biological denitrification has limited waste demands due to the conversion of nitrate to nitrogen gas. Waste sludge, consisting of biological solids and residual organic matter, requires appropriate disposal;
however, with nearly 100% water recovery, the low waste volumes are not a significant burden (Kapoor & Viraraghavan, 1997).

### 3.4.1.9 Maintenance, Monitoring, and Operational Complexity

Because biological denitrification is microbially mediated, to maximize performance, systems should be run continuously, with a consistent supply of substrate and nutrients at the appropriate dosage (Dördelmann, 2009). An initial startup period may be necessary for development and acclimation of the microorganisms (Holló & Czakó, 1987; Aslan, 2005). This may be problematic for intermittent use of wells and wasting may be required for acclimation to occur. Backwashing, consistent maintenance and regular monitoring of product water quality are also essential. Constituents that should be monitored frequently are nitrate, nitrite, pH, oxygen, turbidity, conductivity, dissolved organic carbon, and bacterial count (Dördelmann, 2009). Operation and maintenance demands of biological denitrification systems typically exceed those of alternative treatment technologies. However, these systems are more sustainable because nitrate is reduced to innocuous nitrogen gas rather than concentrated in a waste stream that requires costly disposal (Dördelmann, 2009).

### 3.4.2 Biological Denitrification - Cost Considerations

For efficient operation of a biological denitrification system, maintaining optimal conditions for the bacteria is essential, as is balancing the appropriate substrate and nutrient dose and managing pre and post-treatment while meeting necessary potable water guidelines. Factors affecting system cost include facility size (flow rate), source water quality (including nitrate concentration), environmental factors (temperature and pH), target effluent nitrate concentration, and possible wasting due to intermittent use of wells and associated acclimation of microorganisms.

Capital costs for biological denitrification include land, housing, piping, storage tanks, O&M equipment, preliminary testing (through extensive pilot studies), permits, and significant operator training. O&M costs include post-treatment, sludge disposal, chemical use (pH adjustment, substrate and nutrient), repair, extensive monitoring and maintenance, power, and labor. Costs can be higher in certain states, depending on post-treatment requirements.
Very little published cost information from existing biological denitrification systems for drinking water is available in the literature, due to the limited number of full-scale systems (Table 3-13). Costs have been adjusted to 2010 dollars, unless indicated otherwise. The listed cost information is provided as an approximate range of costs for specific facilities. Costs for implementing biological denitrification may be very different from those listed here. A thorough cost analysis of design parameters for specific locations would be required for accurate cost estimation. The information gathered through the questionnaire includes detailed costs associated with the individual case studies included in this analysis.

Table 3-13 Cost Information* for Biological Denitrification of Potable Water.

<table>
<thead>
<tr>
<th>System Flow**</th>
<th>&lt; 0.5 MGD</th>
<th>0.5 – 5 MGD</th>
<th>5+ MGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annualized Capital Cost ($/1000 gal)</td>
<td>0.83 [1]</td>
<td>0.61 – 0.80 [2, 3]***</td>
<td>0.51 – 0.62 [4]</td>
</tr>
<tr>
<td>O&amp;M Cost ($/1000 gal)</td>
<td>0.30 [1]</td>
<td>0.33 – 0.46 [2, 3]***</td>
<td>0.74 – 0.94 [4]</td>
</tr>
<tr>
<td>Total Annualized Cost ($/1000 gal)</td>
<td>1.13 [1]</td>
<td>1.03 – 1.13 [2, 3]***</td>
<td>1.25 – 1.56 [4]</td>
</tr>
</tbody>
</table>

*Costs have been adjusted to 2010 dollars with 7% interest over 20 years, unless indicated otherwise.
**When available, costs are based on actual system flow rather than design capacity.
***Listed costs are based on biological treatment for perchlorate and should be considered only as a rough estimate of similar systems for nitrate treatment.

3.4.3 Biological Denitrification - Selected Research

Table A.4 of the Appendix is a list of recent research studies relevant to the use of biological denitrification in potable water treatment.

3.4.4 Biological Denitrification - Summary of Advantages and Disadvantages

A summary of advantages and disadvantages of biological denitrification in comparison with other treatment options is listed in Table A.6 of the Appendix. Advantages of the use of biological denitrification for nitrate removal from potable water include high water recovery, no brine or concentrate waste stream (reduction of nitrate rather than removal to a concentrated waste stream), low sludge waste, less expensive operation, limited chemical input, multiple contaminant removal, and increased sustainability (Brown, 2008; WA DOH, 2005; and Upadhyaya, 2010).
Disadvantages of nitrate removal using biological denitrification are post-treatment requirements for the removal of biomass and dissolved organics, high capital costs, potential sensitivity to environmental conditions (although recent pilot tests indicate robust newer designs), system footprint larger than typical IX systems, high system complexity (may be simplified with new configurations), lack of full scale systems in the U.S., potential for incomplete denitrification, pilot study requirements, and slow start-up (Kapoor & Viraraghavan, 1997 and WA DOH, 2005).

3.4.5 Biological Denitrification - Case Studies

The following case studies provide detailed information on the design and operation of a pilot-scale and planned full-scale biological treatment systems that can be used for nitrate removal.
System Description

The West Valley Water District (District) utilizes 2 surface water sources and 5 groundwater wells. Of these supplies, one groundwater well is impacted by nitrate contamination above the MCL, with an average nitrate concentration of 18 mg/L of nitrate as N. The well source is the Chino Basin which has an estimated capacity of 300-400K ac. ft. For the immediate future this well has been abandoned due to nitrate contamination, while feasible treatment options are being explored. The primary water quality concern in the District is perchlorate contamination. Biological denitrification has been explored principally to address perchlorate levels typically in the range of 50-53 μg/L. However, simultaneous nitrate reduction in the biological denitrification process makes this system an appropriate example as a nitrate treatment alternative.

Unlike the removal processes of IX, RO and EDR, biological denitrification allows for the destruction of nitrate through reduction to innocuous nitrogen gas. The fluidized bed configuration maximizes media surface area for the growth of denitrifying bacteria. After a successful 1-year demonstration study on well Rialto #2, a full scale Fluidized Bed Bioreactor (FBR) is expected to be online in early 2012.

“...The system is the fluidized bed bioreactor (FBR). The contaminated feed water is pumped from the wellhead and fed directly into a recycle line of the reactor. The feed and recycle water enters the vessel through an inlet header at the bottom of the reactor and is distributed through lateral piping and nozzles. The fluid passes upward through the media, causing the media to hydraulically expand approximately 28% of the settled bed height. Through a self-inoculating process from the contaminated feed water, microorganisms attach on to the fluidized media. Adequate quantities of electron donor (i.e., acetic acid) and nutrients are added to the reactor. Utilizing this electron donor and the nutrients, the attached microorganisms perform an oxidation/reduction reaction in consuming all of the dissolved oxygen, nitrate, and perchlorate. As the microorganisms grow, the amount of attached microbes per media particle also increases. Since the microbes primarily consist of water, the volume of the microbe/media particle increases, but the specific density decreases. This allows the media bed to expand and fluidize further such that longer hydraulic detention times can be achieved for contaminant removal. The treated fluid flows into a submerged recycle collection header pipe and the effluent collection header pipe at the top of the reactor. A portion of the fluid exits the FBR system to a post-aerator while the balance is recycled back to the suction of the influent pump. An in-bed biomass separation device controls bed height growth by physically separating biomass from the...
media particles. Typically, a bed expansion of 40-60% of the settled bed height is targeted. Any excess biomass that is separated from the media exits the system through the effluent collection system” (Webster & Togna, 2009).

Source Water Quality

- Nitrate (mg/L N)
  - Demonstration well: 6.2-6.3
  - Abandoned nitrate impacted well: 18

- Co-contaminants: Perchlorate
  - Demonstration well: 50-53 μg/L, spiked to 1000 μg/L (with appropriate substrate and nutrient adjustments)
  - Abandoned nitrate impacted well: a few ppb

Treatment Technology Selection

The fluidized bed bioreactor was selected for perchlorate removal; however, nitrate reduction is also accomplished. Due to the levels of nitrate and perchlorate, biological denitrification was deemed to be more cost-effective than alternative physico-chemical technologies. Generally, with nitrate levels well above the MCL (e.g., 100 mg/L as nitrate), removal processes can become more costly. Biological denitrification can be the more feasible option for source water containing co-contaminants and/or high levels of nitrate.

For the Rialto #6 and West Valley Water District #11 wells, the fluidized bed reactor and IX were considered. Two additional pilot studies were performed to assess nitrate and perchlorate treatment using a packed bed bioreactor and zero valent iron.

Demonstration System Parameters

- Design Capacity
  - 50 gpm capacity

- Pretreatment
  - Substrate and nutrient addition
    - Acetic Acid: 16.2 mg/L as C (+20-25%) 15 mL/min, 50% acetic acid
  - Nutrient addition
    - Phosphoric Acid: 0.3 mg/L as P 10.5 mL/min

- Post-treatment
  - Aeration tank
    - Increase dissolved oxygen
  - Clarifier/multimedia filter
  - GAC filtration
  - UV disinfection versus chlorination

- Water Recovery: > 99%
- Bed Expansion:
  - 28% of settled bed height
  - Max: 40-60%
- Media: Sand or GAC
- Cleaning requirements
  - Biomass separator
  - In-bed cleaning eductor
- Manufacturer: Envirogen Technologies, Inc.
- Monitoring: Throughout the demonstration using online nitrate and perchlorate analyzers
Demonstration System Cost Estimation - Scaling up from 50 gpm to 1000 gpm

<table>
<thead>
<tr>
<th>Capital Costs (2008 dollars) (1000 gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Equipment Costs</td>
</tr>
<tr>
<td>Total Contractor Costs</td>
</tr>
<tr>
<td>Total Home Office Costs</td>
</tr>
<tr>
<td>Total Installed Capital Costs (1000 gpm)</td>
</tr>
<tr>
<td>Amortized Capital Cost ($/AF)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O &amp; M Costs (2008 dollars) (1000 gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity ($/yr)</td>
</tr>
<tr>
<td>Chemicals ($/yr)</td>
</tr>
<tr>
<td>Maintenance ($/yr)</td>
</tr>
<tr>
<td>Total Operating Costs ($/yr)</td>
</tr>
<tr>
<td>Operating Costs ($/AF)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Cost (2008 dollars) (1000 gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Annualized Cost ($/AF)</td>
</tr>
</tbody>
</table>

Proposed Full Scale System Parameters

- **Design Capacity**
  - 2000 gpm capacity
  - Expandable to 4000 gpm

- **Pretreatment**
  - Substrate and nutrient addition
    - Acetic Acid: 10-15 mg/L as C

- **Post-treatment**
  - Aeration tank
    - Increase dissolved oxygen
  - Clarifier/multimedia filter
  - Chlorine disinfection

- **Treatment system footprint**
  - Treatment system: 2 FBRs
    - 14' diameter x 24’ height
  - Residuals handling system
    - DAF for solids removal
  - Total system footprint:
    - For 4000 gpm
      - 180’ x 130’
    - For 2000 gpm
      - 25% less than above

- **Water Recovery**: > 99% expected
- **Bed Expansion**:
  - 28% of settled bed height
  - Max: 40-60%
- **Media**: Sand or GAC
- **Cleaning requirements**
  - Biomass separator
  - In-bed cleaning eductor
- **Manufacturer**:
  - Envirogen Technologies, Inc.
- **Monitoring**: N/A
- **Waste Volume**:
  - 0.3 gpm waste per 2000 gpm treated
Proposed Full Scale System Cost Estimation

<table>
<thead>
<tr>
<th>Capital Costs (Total with explanation or component costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment and Monitoring Equipment:</td>
</tr>
<tr>
<td>$1.8 million for the 2 FBR vessels, the 2 post-aeration vessels, nitrate and perchlorate monitoring, 1 DAF, chemical feed systems, pumps, valves, additional components</td>
</tr>
<tr>
<td>Filtration System:</td>
</tr>
<tr>
<td>$800,000 for the 2 clarifier and multimedia filters</td>
</tr>
<tr>
<td>O &amp; M Costs (Total with explanation or component costs)</td>
</tr>
<tr>
<td>Unavailable because system is not yet operating.</td>
</tr>
<tr>
<td>Please see above for estimated O &amp; M costs from the full-scale demonstration study.</td>
</tr>
</tbody>
</table>

Residuals Management

Unlike removal technologies, the use of the FBR results in destruction of nitrate and perchlorate, rather than the transfer of these constituents to a concentrated waste stream requiring disposal.

Technology Benefits and Drawbacks

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Capable of perchlorate removal and handling high nitrate levels</td>
<td>• Limited application in the U.S.</td>
</tr>
<tr>
<td>• Reduction of nitrate rather than just removal</td>
<td>• Large system footprint</td>
</tr>
<tr>
<td>• High water recovery and limited waste</td>
<td>• More complicated permitting</td>
</tr>
<tr>
<td>• Lower operating costs than removal technologies</td>
<td>• Extensive pilot study necessary</td>
</tr>
<tr>
<td></td>
<td>• Start-up time (up to a month)</td>
</tr>
<tr>
<td></td>
<td>• Increased operator attention</td>
</tr>
<tr>
<td></td>
<td>• Sensitivity to system interruption</td>
</tr>
</tbody>
</table>

Additional Information

The full scale system is being planned specifically to address perchlorate contamination, but will reduce nitrate as well. The proposed start-up date for the full scale system is Late-2011 to Early-2012. Construction has begun and all equipment is scheduled to be in place by December of 2011. The system should be fully operational with discharge to groundwater by Mid-2012. With approval from the California Department of Public Health (CDPH) it is expected that distribution of treated drinking water will begin by the end of 2012. Regarding operator training, for this system, the operators already held the required certification due to operation of a surface water treatment plant; however, for other utilities lacking this pre-existing experience, additional training would likely be needed.
Regarding permitting, the 97-005 process from the CDPH Policy Memo 97-005, (“Guidance for the Direct Domestic Use of Extremely Impaired Sources”) was followed as guidance for the FBR installation. The 97-005 process is strenuous and involved, requiring analysis of failure and worst-case scenarios and a 6 month demonstration of proper operation of the treatment plant. The system sizes for which a FBR would be appropriate vary with the concentration of contaminants. Feasible application of a FBR can be more dependent on load than on flow capacity. The FBR has been implemented or tested for systems as small as 7 to 12 gpm and across perchlorate concentrations from 12 to 13000 ppb. Typical flow rates are 250 to 5000 gpm, but with high loads FBRs can become more feasible for lower flow rates.

Source*

Webster, T.S. and Crowley, T. (October, 2010). Completed questionnaire and personal communication.

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.
System Description

The Western Municipal Water District (Western) operates the Arlington Desalter as a drinking water supply facility. The original RO water treatment facility was constructed in the late-1980s for salt management in the Arlington groundwater basin. In 2002 the facility was upgraded and subsequently approved as a potable water supply by the California Department of Public Health (CDPH). Three wells supply raw water to the RO process and two additional wells supply bypass water for blending with the RO permeate to produce the finished water (product water).

The current capacity of the Arlington Desalter is 5 million gallons per day (MGD) of RO permeate and approximately 1.3 MGD of untreated bypass for a total product water capacity of 6.3 MGD. Western’s water supply reliability program, developed through the Integrated Regional Water Management Plan (IRWMP), includes plans for expansion of the Arlington Desalter to 10 MGD capacity.

A pilot study was conducted at the Arlington Desalter from April through November 2007 that demonstrated the feasibility of nitrate removal using fixed bed biological treatment (biodenitrification) of the RO bypass stream. After completion of the initial pilot study, CDPH proposed a turbidity standard for the biodenitrification process. Supplemental pilot testing conducted between May and September 2008 demonstrated compliance with the new turbidity standard by adding a nitrogen degasification step followed by coagulation and polishing filters.

The FXB biological process utilizes a stationary bed of granular activated carbon (GAC) on which biofilms containing nitrate-reducing bacteria develop. Raw water is drawn from a well amended with an electron donor such as acetic acid. The water is then pumped through the GAC bed. Bacteria in the bed convert the nitrate to nitrogen gas and water. A one-time acclimation period is required to develop the nitrate-reducing biological activity, which is done by contacting virgin GAC with raw water and acetic acid for two to three weeks. The denitrifying bacteria used in the system are indigenous to the natural groundwater, meaning the system is naturally seeded with bacteria present in the groundwater.

During the pilot, a clone library analysis was performed on the bacteria within the biofilter to classify the various types of denitrifying bacteria present. The analysis revealed a diverse community of bacteria. At least 10 different denitrifying genera were identified, including Acidovorax, which comprised approximately 37 percent of the total bacteria in the FXB biofilters. The bacteria identified were gram negative, suggesting that they would be particularly sensitive to chemical disinfection, as gram-negative bacteria tend to have thin cell walls.

Source Water Quality

- Nitrate (mg/L N)
  - Average – 17
  - Minimum – 10
  - Maximum – 20

- Co-contaminants
  - Perchlorate: 6 µg/L
  - DBCP: 0.025 µg/L
Treatment Technology Selection

The FXB process has been used successfully for removal of nitrate from drinking water supplies in Europe for decades, but has not yet been used full-scale in the United States. Reasons for using the FXB process at the Arlington Desalter include the following:

- Nitrate is not concentrated in a waste stream, as in RO or IX treatment, but is converted to nitrogen gas, which is released to the atmosphere—a harmless emission because the atmosphere is 78 percent nitrogen.
- Nitrate removal efficiencies are high. Typically, greater than 90 percent removal was achieved during the Arlington pilot studies and removal to non-detect levels was possible.
- The biodenitrification process results in simultaneous destruction of some anthropogenic contaminants. For example, perchlorate, found in the Arlington Desalter supply, was reduced to non-detect levels in the pilot study.

Historically, IX treatment has been the process of choice for nitrate removal in this country; however, it results in the replacement of nitrate with chloride in the drinking water supply. It is estimated that the equivalent IX system installed at the Arlington Desalter would add approximately 3 million pounds of salt to the basin annually. The removal of salt was the purpose for construction of the Arlington Desalter in the first place.

Treatment System Parameters

- Design Capacity
  - 1,670 gpm capacity
- Pretreatment
  - Substrate and nutrient addition
- Post-treatment
  - Degasification of N₂ removal
  - Filtration for compliance with SWTR
- Water Recovery: expected 95%
- Media: GAC
- Treatment system footprint: TBD

Residuals Management

The residuals from this process, primarily biological growth, are accumulated in the filtration process. Once a predetermined pressure loss is experienced in filtration, the filters are backwashed to remove the accumulated solids. The solid laden backwash is then sent to the Santa Ana Regional Interceptor (SARI) line and ultimately disposed of off shore.
Technology Benefits and Drawbacks

**Benefits**
- Less expensive than other technologies
- No disposal of waste brine
- High water recovery rate: > 95%
- Can remove co-contaminants

**Drawbacks**
- No full-scale applications in operation
- More complicated permitting

Treatment Technology Costs

Detailed cost estimates are being developed. Detailed design of this system may occur in 2012, and full-scale construction of this system may be in 2013.

As an approximation, the below costs are based on a fixed-bed demonstration system for the removal of perchlorate with a similar EBCT (Carollo Engineers, 2008).

<table>
<thead>
<tr>
<th>Capital Costs (2008 dollars)</th>
<th>1000 gpm</th>
<th>2000 gpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total:</td>
<td>$4,193,000</td>
<td>$7,395,000</td>
</tr>
<tr>
<td>Direct Installed Costs:</td>
<td>$2,373,000</td>
<td>$4,200,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O &amp; M Costs (2008 dollars)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Estimated Annual O&amp;M Costs:</td>
<td>$175,000</td>
<td>$348,000</td>
</tr>
<tr>
<td>Chemicals ($/yr):</td>
<td>$161,000</td>
<td>$323,000</td>
</tr>
<tr>
<td>Other (GAC and Filter Sand) ($/yr):</td>
<td>$9,000</td>
<td>$17,000</td>
</tr>
<tr>
<td>Power ($/yr):</td>
<td>$5,000</td>
<td>$8,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Costs (2008 dollars, 2.8% discount rate, 30-year lifecycle)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amortized Project Costs:</td>
<td>$209,000</td>
<td>$368,000</td>
</tr>
<tr>
<td>Estimated Annual Budget:</td>
<td>$384,000</td>
<td>$716,000</td>
</tr>
<tr>
<td>Total Treatment Costs ($/1000-gal):</td>
<td>$0.73</td>
<td>$0.68</td>
</tr>
<tr>
<td>Total Treatment Costs ($/AF):</td>
<td>$238</td>
<td>$222</td>
</tr>
</tbody>
</table>

*Source*:
Bernosky, J. 2010. Personal communication.

*Unpublished sources used in the development of the case studies are not reflected in the References section of this report.*
3.5 Chemical Denitrification (CD)

Chemical denitrification can be accomplished with reduction of nitrate by metals. Various metals have been investigated for use in nitrate reduction including aluminum and iron (both $Fe^0$ and $Fe^{2+}$), while copper, palladium and rhodium can be used as catalysts in nitrate reduction (Shrimali & Singh, 2001). The advantage of chemical denitrification over the removal technologies is that nitrate is converted to other nitrogen species rather than simply displaced to a concentrated waste stream that requires disposal. Problems with chemical denitrification of potable water are the reduction of nitrate beyond nitrogen gas to ammonia, partial denitrification and insufficient nitrate removal (nitrite can be converted to nitrate with the use of chlorine in disinfection). No full-scale chemical denitrification systems have been installed in the United States for the removal of nitrate in potable water treatment. A significant body of research has explored the use of zero valent iron (ZVI) in denitrification. Several patented granular media options are also emerging, including SMI-III® (Sulfur Modified Iron), MicroNose™ Technology, and Cleanit®-LC.

Based on lab and pilot scale studies, there is much variation in the configuration of chemical denitrification systems for nitrate removal from potable water. The generic mechanism of denitrification involves the transfer of electrons from an electron donating metal to nitrate. As in biological denitrification, nitrate is reduced in accordance with Eqn. 9. However, in contrast with biological denitrification, using chemical denitrification, the nitrogen in nitrate is often reduced to the least oxidized form, ammonium (Eqn. 9a) (Hao et al., 2005; and Huang et al., 1998).

\[
\begin{align*}
\text{NO}_3^- & \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2 \\
\text{NO}_3^- & \rightarrow \text{NO}_2^- \rightarrow \text{NH}_4^+ \\
\end{align*}
\]

(Eqn. 9)

Nitrate is exposed to an electron donating metal by passing the treatment stream through granular media. Particle size, surface area and surface chemistry are important media characteristics related to the efficiency of nitrate removal.
3.5.1 Zero Valent Iron (ZVI)

Due to the extensive research focused on the use of zero valent iron (ZVI), ZVI will serve as a preliminary example. There is some variation in the use of ZVI. Forms of application include powdered iron, stabilized iron as nanoparticles, iron filings and permeable reactive barriers (PRBs). Relevant reactions are listed in Eqns. 13 to 18 (Hao et al., 2005; Huang et al., 1998; and Xiong et al., 2009). Nitrate can be reduced to nitrite (Eqn. 14), ammonia (Eqn. 15) or nitrogen gas (Eqn. 18) by ZVI. Following nitrate reduction to nitrite, nitrite can then be reduced to ammonia (Eqn. 17). Nitrate can also be reduced by the hydrogen gas that is produced from corrosion reactions (Eqn. 13) to ammonia (Eqn. 16).

\[
\begin{align*}
\text{Fe}^0 + 2H^+ & \rightarrow H_2(g) + \text{Fe}^{2+} \quad \text{(Eqn. 13)} \\
\text{Fe}^0 + \text{NO}_3^- + 2H^+ & \rightarrow \text{Fe}^{2+} + \text{NO}_2^- + \text{H}_2\text{O} \quad \text{(Eqn. 14)} \\
4\text{Fe}^0 + \text{NO}_3^- + 10H^+ & \rightarrow \text{NH}_4^+ + 4\text{Fe}^{2+} + 3\text{H}_2\text{O} \quad \text{(Eqn. 15)} \\
\text{NO}_3^- + 4\text{H}_2 + 2H^+ & \rightarrow \text{NH}_4^+ + 3\text{H}_2\text{O} \quad \text{(Eqn. 16)} \\
3\text{Fe}^0 + \text{NO}_2^- + 8H^+ & \rightarrow 3\text{Fe}^{2+} + \text{NH}_4^+ + 2\text{H}_2\text{O} \quad \text{(Eqn. 17)} \\
5\text{Fe}^0 + 2\text{NO}_3^- + 6\text{H}_2\text{O} & \rightarrow \text{N}_2(g) + 5\text{Fe}^{2+} + 12\text{OH}^- \quad \text{(Eqn. 18)}
\end{align*}
\]

The reduction of nitrate by iron is characterized by an increase in pH and consumption of hydrogen ions. pH is a significant controlling factor for this treatment method (Hao et al., 2005). The kinetics of nitrate reduction by ZVI have been thoroughly covered in the literature to determine the reaction rate under various conditions. For example, Alowitz & Scherer (2002) examined the nitrate reduction rates of three types of iron. Findings indicate that reduction rate increases with decreasing pH. Huang et al. (1998) investigated the use of powdered zero-valent iron (ZVI) for the reduction of nitrate to ammonia. Highly pH dependent, nitrate reduction was kinetically favorable only at a pH below 4. The minimum ratio of iron to nitrate was 120 m\(^2\)/mol NO\(_3^-\) for complete reduction within 1 hour. Nitrate reduction by ZVI can be optimized through pretreatment of iron particles. High temperature exposure to hydrogen gas and deposition of copper were explored separately as options for pretreatment of the iron surface (Liou et al., 2005). Both methods resulted in improvement of nitrate reduction in almost neutral solutions. The mechanism of improvement is due to the surface chemistry of iron. With a buildup of a surface oxide layer, the availability of sites for nitrate reduction decreases. Hydrogen gas pretreatment reduces the oxide layer, while deposited
copper serves as a catalyst for the transfer of electrons. In their investigation of stabilized ZVI nanoparticles, Xiong et al. (2009) found that the end product of denitrification (nitrogen gas versus ammonium) could be controlled by the iron to nitrate ratio and the use of catalysts.

**Figure 3-12 Surface Chemistry of ZVI Particles (Chui, 2009).**

Examination of the surface chemistry of ZVI particles is of the utmost importance to model and understand its use in the reduction of nitrate. Illustrated in Figure 3-12, relevant factors include: corrosion of ZVI, complexation with water, surface complexation, reduction, precipitation and adsorption. In the corrosion of ZVI, the formation of “green rusts” and “suspended green particles” is associated with stabilization of pH and steady decrease in nitrate (Choe et al., 2004). For nitrate reduction to occur, contact with the reducing agent is required. Reduction of nitrate by ZVI or by any surface bound species requires access to surface sites. Competition for surface sites can impede nitrate reduction; Moore & Young (2005) examined chloride as a potential competitor. Results indicate a minimal impact on nitrate removal; however, other competing ions could be important regarding both competition for adsorption sites and reduction.
3.5.2 Catalytic Denitrification
An extension of chemical denitrification, catalytic denitrification involves metal reduction of nitrate in the presence of a catalyst. Extensive research has investigated catalytic denitrification which may become more readily applicable to potable water treatment with further advances (Reddy & Lin, 2000; Chen et al., 2003; Constantinou et al., 2007; Gavagnin et al., 2002; Lemaignen et al., 2002; Palomares et al., 2003; Pintar et al., 2001; Pintar, 2003; Pirkanniemi & Sillanpaa, 2002; and Sun et al., 2010.)

3.5.3 Chemical Denitrification - Design Considerations
Table 3-14 summarizes key design considerations in the application of chemical denitrification for nitrate removal from potable water.
Table 3-14 Summary of Design Considerations for Chemical Denitrification.

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>• pH adjustment</th>
</tr>
</thead>
</table>
| Post-Treatment | • Filtration for iron removal  
• pH adjustment  
• Chlorine addition for disinfection and oxidation of iron  
• Gas stripping, breakpoint chlorination (for ammonia) |
| Chemical Usage | • pH adjustment (acids and bases)  
• Disinfection and oxidation of iron (chlorine) |
| O&M | • Constant monitoring required to ensure efficient nitrate reduction  
  ○ Nitrate levels  
  ○ Oxidation reduction potential (ORP)  
• Monitoring of nitrite and ammonia will also be necessary due to the potential for incomplete denitrification  
• Management of chemicals  
  ○ pH adjustment  
  ○ Disinfection  
• Waste media and backwash water storage and disposal |
| System Components/Design Parameters | • Ratio of electron donor to nitrate for desired removal  
• Hydraulic Loading Rate (HLR), Empty Bed Contact Time (EBCT)  
• Reactor configuration (upflow, downflow, in series, in parallel)  
• Gas stripping, breakpoint chlorination to remove ammonia (if ammonia is the end-product)  
• Monitoring equipment  
• Filtration to remove iron  
• pH adjustment (decreased in pretreatment and increased before distribution)  
• Disinfection |
| Waste Management and Disposal | • Spent media disposal  
• Iron sludge management  
• Backwash water  
• No waste brine or concentrate as in removal processes |
| Limitations | • No examples of full-scale application for nitrate treatment  
  ○ Unknown reliability for full-scale treatment  
  ○ Unknown costs and operational complications  
• Potential for incomplete denitrification |

### 3.5.3.1 Water Quality

The performance of chemical denitrification systems can be affected by pH, temperature, potential interference by co-contaminants, and the availability of surface sites. The reduction of nitrate by iron is characterized by an increase in pH and consumption of hydrogen ions. pH is a significant controlling factor for this treatment method (Hao et al., 2005). Alowitz & Scherer (2002) examined the nitrate reduction rates of three types of iron. Findings indicate that reduction rate increases with decreasing pH. If nitrate in the water does not come in contact with the electron donor, then reduction will not be possible. The build-up of precipitates can
negatively impact nitrate reduction. The appropriate iron to nitrate ratio will be based on influent and target nitrate concentrations. Product water quality will require monitoring for nitrate, nitrite and ammonia.

3.5.3.2 System Components and Site Considerations

Major system components include chemical storage (for pH adjustment and disinfection), the column containing the media, and post-treatment disinfection. With reduction to ammonia, post-treatment ammonia stripping may also be necessary. Design constraints include temperature, long EBCTs, avoidance of incomplete denitrification, determination of the appropriate iron to nitrate ratio, “chlorine demand to oxidize the released iron,” (DSWA, 2010) and nitrate, nitrite and ammonia monitoring.

3.5.3.3 Residuals Management and Disposal

In contrast to IX and membrane technologies, the burdens of brine and concentrate disposal are minimized because nitrate is reduced rather than removed. There is no concentrated brine solution requiring costly disposal. However, disposal of backwash water, spent media, and iron sludge is necessary.

3.5.3.4 Maintenance, Monitoring and Operational Complexity

With the possibility of incomplete denitrification, monitoring is required to ensure that product water does not contain high levels of ammonia or nitrite. Exposure of these nitrogen species to chlorine in disinfection or oxygen downstream can lead to nitrification (oxidation back to nitrate) in the distribution system, unless controlled. Additional O&M demands include management of chemicals (acids, bases and chlorine), backwashing the column to maintain flow and performance, and waste management. Despite having no full-scale installation for comparison, overall, chemical denitrification may potentially be less operationally complex than biological denitrification.
3.5.4 Chemical Denitrification - Emerging Technologies

3.5.4.1 Sulfur-Modified Iron (SMI) Media

Chemical reduction of nitrate has been demonstrated for potable water treatment using sulfur-modified iron granular media (DSWA, 2010). Certified to the NSF/ANSI Standard 61 for use in drinking water treatment, SMI-III® is a patented media that is recyclable and offers the advantage of multiple contaminant removal (SMI-PS, 2009). Arsenic and metals can be removed via adsorption (Cr(VI) can also be reduced and precipitated), while nitrate is reduced to ammonia (Prima Environmental) or nitrogen gas (DSWA, 2010). “The SMI-III® manufacturer believes sulfur modification regulates the environment of reactions to achieve greater and a consistent nitrate reduction” (DSWA, 2010). Nitrate reduction is governed by the following reactions (SMI-PS, 2009):

\[
\begin{align*}
4\text{Fe}^0 + \text{NO}_3^- + 10\text{H}^+ & \rightarrow 4\text{Fe}^{2+} + \text{NH}_4^+ + 3\text{H}_2\text{O} \quad \text{(Eqn. 19)} \\
5\text{Fe}^0 + 2\text{NO}_3^- + 12\text{H}^+ & \rightarrow 5\text{Fe}^{2+} + \text{N}_2 + 6\text{H}_2\text{O} \quad \text{(Eqn. 20)}
\end{align*}
\]

Key advantages of SMI-III® are the ability to remove multiple contaminants simultaneously and the limited waste disposal costs relative to other nitrate removal options (no brine waste stream is produced) (DSWA, 2010). Some previous research indicates inconsistent and insufficient nitrate removal to meet potable water regulations (DSWA, 2010).

DSWA and the City of Ripon, California conducted a pilot study investigating the use of SMI-III® in potable water treatment. Findings suggest that this treatment option may be suitable for source nitrate concentrations slightly above the MCL (up to 15.07 mg/L as N (70 mg/L as nitrate)). Phase A of the pilot study was operated with the SMI-III® media in an up-flow fluidized bed across a pH range of 6.0-6.8 and with an EBCT of 15 to 30 minutes, while phase B tested improved media performance across the same pH range and with an EBCT of 30 minutes. Figure 3-13 displays a process schematic of the SMI-III® process.
The media was fluffed (backwashed in upflow mode) daily to remove oxidized iron and to avoid media agglomeration. The SMI-III® reactor was followed by coagulation and filtration for the removal of iron, arsenic and other constituents. In phase A, the greatest nitrate removal (3.88 mg/L as N, 18 mg/L as nitrate) was insufficient to meet the 20% safety margin of the project (a goal of 7.75 mg/L as N, 36 mg/L as nitrate), with a starting nitrate concentration of 12.92 mg/L as N (60 mg/L as nitrate). Problems in phase B resulted in operation interruption; however, a maximum nitrate removal of 5.17 mg/L as N (24 mg/L as nitrate) was achieved. When the pH was reduced to 6, the system did produce water with nitrate below the MCL and the project goal nitrate level, on two occasions. Temperature was found to have the most significant impact on removal efficiency. Nitrate reduction improved with increasing source water temperatures.

Design constraints include temperature, EBCT, avoidance of incomplete denitrification, determination of the appropriate iron to nitrate ratio, “chlorine demand to oxidize the released iron,” clogging from precipitates and pH. Nitrate reduction typically increases with decreasing pH, increasing EBCT and increasing temperature (DSWA, 2010).
SMI - Cost Considerations
Cost analysis in the City of Ripon report included acid, caustic soda and media and excluded labor and waste management. In both phases, minimal variation in nitrate reduction was found with operation at a pH of 6 versus a pH of 6.8. Operation at the higher pH minimizes costs due to prolonging media life and decreasing chemical input. The production costs for operation at a pH of 6 and 6.8 were estimated to be $729/ac.ft. ($2.24/1000 gal.) and $287/ac.ft. ($0.88/1000 gal.), respectively (DSWA, 2010). Due to dissolution of the media over time, media disposal is not expected to be necessary. Dissolved iron is oxidized and then removed through filtration. In the Ripon pilot study backwash water was discharged to the sewer; however, when “…direct sewer disposal is not feasible, the backwash water must undergo solid/liquid separation with the decant liquids recycled to the head of the treatment system and the dewatered solids sent to an appropriate landfill for disposal” (DSWA, 2010). If the waste is deemed hazardous, disposal can be a major cost consideration.

3.5.4.2 Granular Clay Media
Certified to the NSF/ANSI Standard 61 for use in drinking water treatment, MicroNose™ Technology media is currently being examined in Manteca, California for nitrate removal in potable water treatment (MicroNose™). The media consists of “absorbent and permeable pottery granules which function similar to the mucous membrane in the human nose” (University of Hawaii, 2006). Limited information is available on this emerging technology. The company states, “MicroNose™ Technology media removes heavy metals, such as arsenic, manganese, and lead as well as nitrates through non-chemical processes” (MicroNose™). MicroNose™ offers removal of multiple contaminants concomitantly and claims to be cost effective, suitable for nitrate removal and a green technology. Additional information is needed to assess the design considerations, costs and applications of MicroNose™ for nitrate removal from potable water.
3.5.4.3  Powdered Metal Media

As an emerging technology, Cleanit®-LC (from North American Höganäs) is a metal powder with the potential to achieve 60-90% nitrate removal (Lavis, 2010). Certified to the NSF/ANSI Standard 61 for use in drinking water treatment, this proprietary iron-based powder could be used for removal of co-contaminants in addition to nitrate, including “arsenic, heavy metals, phosphates and pathogens” (Lavis, 2010), and potentially hexavalent chromium. Cleanit®-LC media is characterized by the following: a density of 1800-2100 kg/m$^3$, a particle size of 150-850 microns, and a porosity of 60%. The powder can be used to adsorb arsenic in under 10 minutes, with an arsenic capacity of 4 – 8 mg/g powder.

With an up-flow configuration, the treatment stream is pumped through a column containing the media, maximizing surface contact. The most significant consideration is the EBCT. At the particle surface, nitrate is reduced to nitrogen gas with EBCTs of 10 - 30 minutes. Additional key design factors are pH and temperature. In contrast to membrane technologies, the burdens of disposal are minimized because nitrate is reduced rather than removed. There is no concentrated brine solution requiring costly disposal. Preliminary third party results indicate nitrate removal over 7 months to below the MCL (North American Höganäs, data). However, as a new product on the market, further research is required to assess Cleanit®-LC for the removal of nitrate and other constituents in potable water treatment.

3.5.5  Chemical Denitrification - Cost Considerations

For efficient operation of a chemical denitrification system, maintaining efficient nitrate reduction is essential. Optimal performance includes managing pre and post-treatment to provide appropriate environmental conditions, while meeting necessary potable water guidelines. Factors affecting system cost can include facility size (flow rate), source water quality (including nitrate concentration and co-contaminants), environmental factors (temperature and pH), and target effluent nitrate concentration.

Capital costs for chemical denitrification include land, housing, piping, media, storage tanks, O&M equipment, preliminary testing (through pilot studies), permits, and operator training.
O&M costs include pre and post-treatment, media replenishment and disposal, backwashing, chemical use (pH adjustment, chlorine), repair, monitoring, maintenance, power, and labor.

The availability of published cost information for chemical denitrification is strictly limited to pilot scale studies, due to the lack of full scale systems. Cost analysis in the City of Ripon report included acid, caustic soda and media and excluded labor and waste management. In both phases, minimal variation in nitrate reduction was found with operation at a pH of 6 versus a pH of 6.8. Operation at the higher pH minimizes costs due to prolonging media life and decreasing chemical input. The production costs for operation at a pH of 6 and 6.8 were estimated to be $729/ac.ft. ($2.24/1000 gal.) and $287/ac.ft. ($0.88/1000 gal.), respectively (DSWA, 2010). Due to dissolution of the media over time, media disposal is not expected to be necessary. Dissolved iron is oxidized and then removed through filtration. In the Ripon pilot study backwash water was discharged to the sewer; however, when “…direct sewer disposal is not feasible, the backwash water must undergo solid/liquid separation with the decant liquids recycled to the head of the treatment system and the dewatered solids sent to an appropriate landfill for disposal” (DSWA, 2010). If the waste is deemed hazardous, disposal can be a major cost consideration.

3.5.6 Chemical Denitrification - Selected Research

Table A.5 of the Appendix is a list of recent research studies relevant to the use of chemical denitrification in potable water treatment.

3.5.7 Chemical Denitrification - Summary of Advantages and Disadvantages

A summary of advantages and disadvantages of chemical denitrification in comparison with other treatment options is listed in Table A.6 of the Appendix. Advantages of chemical denitrification for nitrate removal from potable water include the conversion of nitrate to other nitrogen species (no brine or concentrate waste stream), the potential for more sustainable treatment, and the ability to remove multiple contaminants.

Problems with chemical denitrification of potable water are the potential reduction of nitrate beyond nitrogen gas to ammonia, the possibility of partial denitrification, and the lack of full-scale chemical denitrification systems.
3.6 Brine Treatment Alternatives and Hybrid Treatment Systems

Brine or concentrate disposal can be a great concern with the use of the removal processes, IX, RO, and ED/EDR, especially for inland communities. Brine treatment and recycling alternatives have the potential to address disposal concerns, improving sustainability and decreasing operating costs. Hybrid systems, combining different nitrate treatment technologies, have been explored to include the advantages of multiple treatment options, while avoiding their respective disadvantages (Kabay et al., 2007; Matos et al., 2006; Pintar et al., 2001; Van Ginkel et al., 2008; and Wisniewski et al., 2001). Table 3-15 lists a selection of additional research related to brine treatment alternatives and the use of hybrid systems to improve nitrate treatment performance.

The combination of denitrification methods with removal technologies enables resolution of common problems with each option. The brine waste stream from IX, for example can be treated using biological denitrification to reduce nitrate to nitrogen gas. Biological denitrification of IX waste brine using an upflow sludge blanket reactor (USBR) was demonstrated at the lab-scale by van der Hoek & Klapwijk (1987). Clifford & Liu (1993) implemented a lab-scale sequencing batch reactor (SBR) for the denitrification of waste brine resulting in the ability to recycle the treated waste brine for 15 regeneration cycles. The SBR process was pilot tested in McFarland, CA (Liu & Clifford, 1996). With denitrification of spent brine followed by reuse, a 95% decrease was achieved in salt waste. Use of a membrane bio-reactor in this context has also been explored (Bae et al., 2002; Van Ginkel et al., 2008; Chung et al., 2007). Through the reduction or destruction of nitrate in spent IX brine, disposal needs may be significantly reduced as treated brine can be repeatedly recycled back for use in resin regeneration. Additionally, through treatment of RO or ED/EDR waste concentrate, removal of nitrate from the waste stream may improve disposal options.
Table 3-15 Selected Research on Brine Treatment Alternatives and Hybrid Systems for Nitrate Treatment of Potable Water.

<table>
<thead>
<tr>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>IX and Catalytic Reduction</td>
<td>Pintar et al. (2001)</td>
</tr>
<tr>
<td>RO and EDR</td>
<td>EET Corporation (2008)</td>
</tr>
<tr>
<td>IX and EDR</td>
<td>Kabay et al. (2007)</td>
</tr>
<tr>
<td>ED and MBR</td>
<td>Wisniewski et al. (2001)</td>
</tr>
<tr>
<td>IX and Biological Denitrification</td>
<td>Clifford &amp; Liu (1993), Van Ginkel et al. (2008), Bae et al. (2002), Van der Hoek &amp; Klapwijk (1987)</td>
</tr>
<tr>
<td>RO and VSEP</td>
<td>Lozier et al. (N.D.)</td>
</tr>
<tr>
<td>Electrochemical destruction of nitrate (in IX brine)</td>
<td>DOW/STWP collaboration (Goltz &amp; Parker, 2010/2011), Dortsiou et al. (2009), and Yu &amp; Kupferle (2008).</td>
</tr>
</tbody>
</table>

3.6.1 Electrochemical Destruction of Nitrate in Waste Brine

Two major companies are developing a system which incorporates IX with electrochemical destruction of nitrate. With the removal of nitrate from spent brine, the brine can be recycled for reuse in regeneration (Goltz, 2010 and Goltz & Parker, 2010/2011). Spent brine is treated following IX treatment. With electricity distributed over a high surface area electrode, upon contacting the electrode surface, nitrate in the brine waste is reduced to nitrogen gas. In the overall reaction, nitrate is reduced and water is oxidized producing nitrogen gas and oxygen. Possible reduction to ammonia/ammonium is accounted for in the process. Laboratory tests have been successful and planning of site tests is underway to examine system performance across a variety of raw water characteristics. The potential benefits of this brine treatment alternative are in the increased sustainability and the decreased disposal costs. The objective is to optimize the process such that the savings on disposal costs, especially for inland communities, outweigh the increased electricity costs of the process.

3.6.2 Catalytic Treatment of Waste Brine

Calgon Carbon is working with the University of Illinois to develop a brine recovery system with the goal of up to 90% brine recovery for reuse using Pd-based catalytic treatment (Drewry, 2010). The following information was provided by Dr. Charles Werth (2010) from the University of Illinois.
As illustrated in Figure 3-14, “The spent brine solution is equilibrated with hydrogen in a gas-liquid membrane, and subsequently treated to remove nitrate in the packed bed catalyst system containing Pd-In on granular activated carbon (GAC). The treated brine is then put back into a holding tank and reused when ion exchange breakthrough occurs again” (Werth, 2010).

Advantages of this brine treatment alternative include conversion of nitrate mainly to nitrogen gas, avoidance of the need for brine waste disposal, and rapid reduction of nitrate with the Pd-based catalyst. Disadvantages include the use of flammable hydrogen gas, some conversion of nitrate to ammonia, “the cost of Pd and potential fouling of the catalyst which requires regeneration using a strong oxidant like hypochlorite (Chaplin et al., 2007)” (Werth, 2010).

Catalytic removal of nitrate has not yet been implemented at the full-scale, but “catalytic systems have been used to remove chlorinated solvents at contaminated groundwater field sites, and they appear to be economically competitive (Davie et al., 2008)” (Werth, 2010). Dr. Werth stated, “Catalytic systems show great promise for removing nitrate from IX brines, but pilot scale studies are needed to evaluate the economic viability.”
3.7 Residential Treatment (Point-of-Use, Point-of-Entry)

Point-of-Use (POU) and Point-of-Entry (POE) water treatment devices can be used to address high nitrate levels and other constituents of concern at the residential scale. A POU treatment device is installed for the purpose of reducing contaminants in drinking water at a single tap, typically the kitchen tap. A POE treatment device is installed for the purpose of reducing contaminants in drinking water entering a house or building.

Treatment technologies for POU and POE systems, used to address nitrate contamination, include IX, RO and distillation (Mahler et al., 2007). IX is generally considered more for POE than for POU and requires disposal of concentrated waste brine. RO systems require more maintenance and have lower water recovery (Mahler et al., 2007). However, according to the New Hampshire Department of Environmental Services (2006), RO “is the most cost effective method for producing only a few gallons of treated water per day” (NHDES, 2006). While distillation can require lower maintenance, energy demands are higher than the other options. Distillation systems are generally intended as POU devices as they remove all minerals and produce water that is aggressive towards plumbing materials.

Certification to the relevant ANSI/NSF standards by an ANSI accredited third party certifier ensures the safety and performance of the residential treatment systems. In the U.S., the following certifiers have been accredited by ANSI to certify drinking water treatment systems:

- Canadian Standards Association International (www.csa-international.org);
- International Association of Plumbing & Mechanical Officials (www.iapmo.org);
- NSF International (www.nsf.org);
- Underwriters Laboratories Inc. (www.ul.com); and
- Water Quality Association (www.wqa.org).

Numerous RO devices for nitrate removal are certified to the ANSI/NSF standard specific to RO POU devices: NSF Standard 58 - Reverse osmosis drinking water treatment systems (NSF, 2009). Additionally, the Water Quality Association, an accredited certifier, lists two POU ion exchange devices for nitrate removal that are certified to NSF Standard 53: Drinking Water Treatment Units – Health Effects (Water Quality Association, 2011). All the technologies listed above are capable of reducing nitrate levels. However, it is important to conduct periodic testing using an
accredited laboratory on both the influent water and the water produced by the treatment system to verify that it is working effectively.

The CDPH provides a list of approved POU devices for nitrate treatment and only RO systems are listed (CDPH, 2009). Published cost information for POU systems is listed in Table 3-16. Based on a survey in Minnesota, “the average cost of nitrate removal systems was $800 to install and $100 per year to maintain” (Lewandowski, 2008). It is important to note that water systems are responsible for meeting federal, state and local requirements and the allowable uses of POU/POE devices vary by state.

Table 3-16  Costs of POU Treatment for Nitrate Removal (from Mahler et al., 2007).

<table>
<thead>
<tr>
<th></th>
<th>Upfront Investment</th>
<th>Annual Costs</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Exchange</td>
<td>$660-$2425[1]</td>
<td>Salt costs ($3.30-$4.40/bag)[1]</td>
<td>Requires disposal of brine waste</td>
</tr>
</tbody>
</table>

Costs have been adjusted to 2010 dollars, unless indicated otherwise. [1] Mahler et al. (2007).
4.0 References


Calgon Carbon Corporation (2007). “Case History: City of Chino: Their Road to Nitrate Removal.”


Dow Water and Process Solutions. See Goltz, Robert.


Envirogen Technologies, Inc. (N.D.). “Case Study: City of Pomona, California.”


Envirogen Technologies, Inc. (N.D.b). “Case Study: Hi-Desert Water District, California.”


References


## 5.0 Appendix

### 5.1 Tables of Selected Research

<table>
<thead>
<tr>
<th>Table A.1: Selected Research on the use of Ion Exchange (IX) for nitrate removal.</th>
</tr>
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<tbody>
<tr>
<td><strong>IX nitrate selective resin</strong></td>
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<tr>
<td><strong>IX adsorption kinetics</strong></td>
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<tr>
<td><strong>IX sulfate competition</strong></td>
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<td><strong>IX co-contaminants</strong></td>
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<tr>
<td><strong>IX Pilot study</strong></td>
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<tr>
<th>Table A.2: Selected research on the use of Reverse Osmosis (RO) for nitrate removal.</th>
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<tbody>
<tr>
<td><strong>RO – Pilot Study and Full scale Installation</strong></td>
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<tr>
<td><strong>RO – HERO in Australia</strong></td>
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<tr>
<td><strong>RO – Pilot study comparing IX, RO and BD</strong></td>
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<tr>
<td><strong>RO – Full scale installations</strong></td>
</tr>
<tr>
<td><strong>RO – Alternative disposal options</strong></td>
</tr>
<tr>
<td><strong>RO – Membrane scaling and fouling, colloidal interaction</strong></td>
</tr>
<tr>
<td>Study Type</td>
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<tr>
<td>------------------------------------</td>
</tr>
<tr>
<td>ED – Pilot study and Full scale installation</td>
</tr>
<tr>
<td>ED – Pilot study – Optimization</td>
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<tr>
<td>EDR – Full scale installation</td>
</tr>
<tr>
<td>EDR – Full scale installation</td>
</tr>
<tr>
<td>EDR – Full scale installations</td>
</tr>
<tr>
<td>ED – Multiple contaminant removal, role of organic matter</td>
</tr>
<tr>
<td>ED – Pilot study</td>
</tr>
<tr>
<td>ED – Pilot study comparison with adsorption</td>
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</table>
Table A.4: Selected research on the use of Biological Denitrification for nitrate removal from potable water.

**Pilot Testing - Multiple Biological Configurations**

The City of Glendale, AZ has investigated three configurations of biological treatment to address high nitrate levels in groundwater wells (Meyer et al., 2010). An autotrophic MBfR using was compared with two heterotrophic fixed bed bioreactors each with different media (plastic versus granular activated carbon). Hydrogen gas and ethanol were used as electron donor for the autotrophic system and the heterotrophic systems, respectively. Post-treatment included filtration using biologically activated carbon and ozonation. The fixed bed bioreactor with plastic media and the MBfR performed well, with product water meeting or exceeding potable water standards. Multi-criteria analysis found the MBfR to be most favorable regarding benefits, but the least favorable regarding costs. Including comparison with IX, the fixed bed bioreactor with plastic media had the lowest life cycle cost. The MBfR costs were greatest.

An investigation of biological treatment options in the City of Thornton, CO, funded by the WaterRF, examined two packed bed bioreactors and a moving bed biofilm reactor (MBBR™) (City of Thornton, 2010, Project # 4202) to address nitrate impacted source water. Nitrate levels were successfully decreased by each of the three pilot systems from an influent concentration of 10 mg/L nitrate as N to an effluent concentration of < 2 mg/L nitrate as N. Operation at high and low temperatures was tested with examination of seeding for low temperatures. The study highlights the need for nutrient and substrate dose optimization in biological treatment systems.

**Substrates**

Numerous alternative substrate options have been explored in the literature including newspapers, vegetable oil, cotton, and formate (Volokita et al., 1996; Hunter, 2001; Della Rocca et al., 2006; Killingstad et al., 2002.)

**Fixed Bed**

See Riverside, CA Case Study (Carollo Engineers, 2008).

A fixed bed heterotrophic denitrification pilot study was implemented in Mashhad, Iran by Dördelmann et al. (2006) using two parallel fixed beds containing expanded clay media. Acetic anhydride and ferrous sulfate served as the electron donor and nutrient supply, respectively. Post treatment consisted of "aeration, dual media and activated carbon filtration" (Dördelmann et al., 2006). Influent nitrate levels of 24.77 mg/L as N (115 mg/L as nitrate) were decreased to < 8.62 mg/L as N (40 mg/L as nitrate) with a nitrate reduction rate of ~7 kg NO\textsubscript{3} /m\textsuperscript{3} d (0.43 lb NO\textsubscript{3} /ft\textsuperscript{3} d) (Dördelmann et al., 2006 and Panglisch et al., 2005). Used for flushing and backwashing, 7% of influent volume was wasted. In practice, a final disinfection step would be required (Dördelmann et al., N.D).

An up-flow, fixed-bed, autotrophic, lab-scale system, using granular sulfur as both substrate and growth surface was explored by Soares (2002). Operated over a 5 month period, a maximum denitrification rate of 0.2 kg N/m\textsuperscript{3} d (0.012 lb N/ft\textsuperscript{3} d) was achieved with a one hour hydraulic retention time and a loading rate of 0.24 kg N/m\textsuperscript{3} d (0.015 lb N/ft\textsuperscript{3} d). Sulfur based autotrophic systems would not be appropriate for the treatment of feed waters high in sulfate.

Aslan (2005) examined a lab-scale packed sand bed system, with ethanol as substrate for the simultaneous removal of nitrate and several pesticides. After 3 days for biofilm development, 93-98% nitrate removal was achieved requiring at least a 2 hour residence time. Pesticide removal required longer residence times (up to 12 hours) for efficient removal.

Upadhyaya et al. (2010) investigated the use of a fixed-bed biological reactor with granular activated carbon media for the removal of nitrate and arsenic at the same time. The media was biologically activated from use in a separate bioreactor for the removal of nitrate and perchlorate. Reactors were thus biologically active carbon (BAC) reactors. With acetic acid as the substrate, two in series BAC reactors were used to treat synthetic groundwater. Arsenic levels were reduced from 200 μg/L arsenic in the influent to 20 μg/L in the effluent (still above the arsenic MCL of 10 μg/L) while nitrate levels were decreased from 10.77 mg/L as N (50 mg/L as nitrate) in the influent to less than 0.043 mg/L as N (0.2 mg/L as nitrate) in the effluent. Used as an electron acceptor by microbes in the oxidation of substrate, nitrate was reduced to nitrogen gas. Arsenic was removed from solution with the formation of arsenic sulfide (solids) and also with adsorption and “surface precipitation on iron sulfides (p. 4958).”

**Fluidized Bed**
Kurt et al. (1987) investigated an autotrophic fluidized sand bed reactor using hydrogen gas as substrate. With an influent nitrate concentration of 25 mg/L nitrate-nitrogen, a maximum nitrate reduction rate of 5 mg/L per hour was attained using a mixed culture. The authors propose multiple stage reactors to address the problem of partial denitrification.

Using a mix of propionic acid and ethanol in a heterotrophic fluidized sand bed reactor, Holló & Czakó (1987) examined denitrification at the lab and pilot scale. Post-treatment consisted of cartridge filtration, gas exchange, sand filtration, carbon filtration and disinfection. “Nitrate removal capacity of the reactor was 50-60 kg NO$_3^-$/m$^3$/day (3.1-3.7 lb NO$_3^-$/gal/d), which could be maintained permanently at temperatures as low as 8-10°C as well” (Holló & Czakó, 1987).

Mansell & Schroeder (2002) assessed hydrogenotrophic denitrification at the lab-scale using a membrane bioreactor (MBR) with a 0.02 micron microporous membrane through which nitrate diffuses to the biological compartment. The membrane prevents mixing of microbes with the water being treated and no carbon substrate was necessary because hydrogen gas was supplied as the electron donor for autotrophic denitrification. Previous issues regarding the transfer of hydrogen gas to the water and safety concerns due to explosive nature of hydrogen gas have been addressed with the development of “membrane dissolution systems” (Mansell & Schroeder, 2002). Hydrogen gas was delivered to the biomass with silicone tubing. Results indicated reduction of nitrate levels from a maximum of 40 mg/L NO$_3^-$ in the feed water to 3.2 mg/L NO$_3^-$ in the treated water, with 92-96% removal. Measured HPC indicated minimal biomass transfer to the treated water compartment.

Ergas & Rheinheimer (2004) studied denitrification of potable water using a membrane bioreactor (MBR) in which feed water is passed through tubular acrylonitrile membranes, nitrate diffuses through the membrane and denitrification occurs on the exterior membrane surface. The mean transfer to the biofilm was 6.1 g NO$_3^-$-N/m$^2$ d (0.6 g NO$_3^-$-N/ft$^2$). The ultimate methanol (substrate) loading rate of 1.1 g/d resulted in a mean concentration of nitrate in the treated potable water of 5.2 mg NO$_3^-$-N/L. A mathematical model of nitrate mass transfer was developed. A removal efficiency of 99% was achieved with a starting concentration of 200 mg NO$_3^-$-N/L. Use of the MBR allows for denitrification with separation of the water to be treated and biological treatment, thereby avoiding post treatment removal of biomass and dissolved organics. The effluent would require additional treatment, because 8% (30 mg/L) of the methanol crossed the membrane; the authors suggest that further development of the biomass could minimize methanol transfer to the effluent stream.

Chung et al. (2007) explored the use of autotrophic denitrification for the treatment of highly concentrated waste from nitrate removal via anion exchange. Using a hydrogen-based, hollow fiber membrane biofilm reactor, the impact of brine concentration (up to 15%) on nitrate reduction was found to be significant due to microbial inhibition. In the reduction of nitrate, use of hydrogen gas rather than an organic substrate offers an inexpensive alternative for potable water treatment systems. Biomass production is decreased and there is no need to remove substrate residual, as there would be with the use of carbon substrates.

Using nitrate as the primary electron acceptor, hollow fiber MBfRs with hydrogen gas as electron donor can effectively decrease the levels of multiple contaminants including perchlorate, chromate and arsenate (Nerenberg & Rittman, 2004). Low levels of these oxidized species without a primary electron acceptor can limit biological reduction; however, in the presence of nitrate, reduction can occur. When the concentrations of nitrate and the oxidized species of interest were 1.08 mg/L as N (5 mg/L as nitrate) and 1 mg/L, respectively, 99% nitrate removal was achieved while removal of perchlorate, chromate and arsenate reached 36%, >75%, and >50%, respectively.

Bioelectrochemical Denitrification

Ghafari et al. (2008) provide a review of biological denitrification with a focus on bioelectrical reactors (BERs). In a BER, hydrogenotrophic denitrification occurs as hydrogen gas is produced at the cathode and utilized as the electron donor by denitrifiers, while nitrate is reduced to nitrogen gas. Previous BER research is discussed including autotrophic and heterotrophic examples across a range of nitrate levels and generally in synthetic waters. With additional research, BERs may become a feasible alternative for nitrate removal from drinking water.

In situ Denitrification

Permeable reactive barriers (PRBs) can be used to directly treat nitrate contaminated groundwater. Hunter (2001) examined the use of vegetable oil as an electron donor.
donor in biological denitrification. The use of an insoluble substrate minimized biomass blockage, a problem common with the use of soluble substrates like ethanol, methanol and acetate. The barrier was composed of soybean oil-coated sand and effectively decreased the nitrate levels from a starting concentration of 20 mg/L nitrate-N to below the MCL for a period of 15 weeks, with a flow rate 1100 L/week. After 15 weeks, insufficient oil remained for denitrification. High chemical oxygen demand, TSS and turbidity in the effluent of the reactor indicate a longer sand bed was needed; however, the author suggests that in situ application of this type of biological reactor would decrease these factors naturally. With a withdrawal point far enough from the barrier, subsequent potable water treatment requirements would be limited to disinfection. The most significant problem encountered in this study was the exhaustion of substrate. An effective means of substrate addition must be found (injection for example), but this was not explored. The estimated life of the PRB was 2.5-12.5 years depending on several key factors including flow, nitrate concentration and dissolved oxygen concentration.

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<th>With hydrogen gas as the substrate in autotrophic denitrification, Haugen et al. (2002) examined hydrogenotrophic denitrification in a lab scale experiment intended to imitate in situ treatment. Denitrification kinetics, the feasibility and longevity of substrate delivery via tubular membranes and post-treatment water quality were investigated. Delivery of hydrogen gas through tubular membranes minimized the risks associated with utilization of this flammable/explosive gas. The reactor was tested over 155 days. An initial influent nitrate concentration of 8.2 mg NO$_3^-$-N/L was doubled to 16.4 mg NO$_3^-$-N/L. After adjustment of parameters, complete nitrate removal was achieved using the tubular membrane bioreactor. A denitrification rate of 169 mg N/h/m$^2$ (membrane surface area) was attained with a hydrogen gas pressure of 1.44 atm (lower pressures resulted in incomplete reduction. The greatest hydrogen gas transfer across the membrane (flux) was 1.79 x 10$^{-2}$ mg H$_2$/m$^2$s. The simulated groundwater velocity was 0.3 m/d resulting in 14 minutes of membrane contact time. Additional considerations for application of this treatment method include: the lower temperature of groundwater, the need for buffer in the current study, the depth limitation, nutrient requirements, and the difference between aquarium rocks and subsurface porous media. Intermediate denitrification products and end products (ammonia and nitrogen gas) were not measured in this study; however, the authors suggest the high nitrate to substrate ratio would result in reduction to nitrogen gas.</th>
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<td>Schnobrich et al. (2007) simulated in situ nitrate removal via hydrogenotrophic Denitrification. With hydrogen gas delivery through a membrane module consisting of a fiberglass membrane wound in a spiral fashion and attached to polyethylene membranes. The study examined the influence of pH, nutrient requirements and the feasibility of appropriate levels of hydrogen gas delivery. To simulate in situ conditions, the porous media was extracted from an aquifer and the system was operated at 10°C. Two upflow columns were operated in series, only the first of which included a membrane fed with hydrogen gas. Including that required for the reduction of dissolved oxygen, the total concentration of hydrogen gas required for complete denitrification was 11.2 mg H$_2$/L. Overall, this study demonstrated effective substrate delivery and nitrate removal under conditions more similar to what would be expected naturally.</td>
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