APPENDIX B

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LIST OF ACRONYMS AND ABBREVIATIONS

AAC	Arizona Administrative Code
A.R.S.	Arizona Revised Statute
APP	Aquifer Protection Permit
FS	Feasibility Study
FFS	Focused Feasibility Study
FFS-Wells	Focused Feasibility Study Wellfield
gpm	gallons per minute
HGC	Hydro Geo Chem, Inc.
IW Wellfield	interceptor wellfield
mg/L	milligrams per Liter
O&M	operation and maintenance
RO	Reverse Osmosis
Sierrita	Freeport-McMoRan Sierrita Inc.
STI	Sierrita Tailing Impoundment
UIC	Underground Injection Control

1. INTRODUCTION

This appendix presents the identification and screening of mitigation response actions, control technologies, and process options potentially applicable for plume management at the Sierrita Tailing Impoundment (STI) operated by Freeport-McMoRan Sierrita Inc. (Sierrita). As used in the Feasibility Study (FS), plume management addresses potential responses to the downgradient sulfate plume. The terms “downgradient sulfate plume” and “downgradient plume” are used in this FS to refer specifically to the portion of the sulfate plume between the existing and proposed source control wellfields and the northern and the eastern margins of the plume (Figure B.1). The source control wellfields consist of the existing interceptor wellfield (IW wellfield) and the wellfield proposed by the Focused Feasibility Study (FFS) (HGC, 2007a). The FFS evaluated ways to improve the capture of seepage from the northern portion of the STI and recommended installation of a wellfield east of the northern portion of the IW wellfield.

This evaluation of plume management assumes the implementation of the source control wellfields to capture STI seepage and control sulfate migration. Although the source control wellfields will capture sulfate from the STI, the downgradient plume will continue to move northward in the absence of additional actions to control plume movement. Plume management can range from no additional action, which would allow the downgradient plume to migrate and sulfate concentrations to naturally attenuate over time, to conducting groundwater pumping to control plume migration. Included in plume management are the associated actions that would be needed to implement a plume management strategy (e.g., institutional actions for exposure management, water management of water pumped for mitigation, and, if needed, water treatment).

Plume management comprises mitigation response actions, control technologies, and process options that are specific techniques that can be used to address the downgradient plume. The purpose of the screening process presented in this Appendix is to identify feasible technologies for plume management for use in developing overall mitigation alternatives for the FS. Hydro Geo Chem, Inc. (HGC) conducted this evaluation of plume management under contract to Sierrita.

2. IDENTIFICATION AND SCREENING OF POTENTIALLY APPLICABLE MITIGATION RESPONSE ACTIONS, CONTROL TECHNOLOGIES, AND PROCESS OPTIONS

Mitigation response actions are general categories of potential response actions (e.g., institutional actions, monitored natural alternation, groundwater control, water treatment, and water management) (Table B.1). Each mitigation response action can consist of one or more control technologies (e.g., groundwater control can be accomplished with groundwater pumping or groundwater barriers). Each control technology can consist of one or more potentially applicable process options (e.g., groundwater pumping can use vertical wells or horizontal wells).

Mitigation response actions, control technologies, and process options potentially applicable to plume management were identified and screened for effectiveness, implementability, and cost. Effectiveness refers to the ability and reliability of the technology or process option to meet the mitigation objective over both short- and long-term time horizons and whether the technology or process option is proven and reliable. Implementability is defined as the technical and regulatory feasibility of implementing a technology or process option at the site, given the general site conditions and regulatory requirements. Effectiveness and implementability were the primary screening criteria. Cost was evaluated qualitatively and used as a secondary screening criterion to discriminate between control technologies and process options with equivalent effectiveness and implementability.

2.1 Mitigation Response Actions

Mitigation response actions for plume management included in the screening are: 1) institutional actions, 2) monitored natural attenuation, 3) groundwater control, 4) water treatment, and 5) water management (Table B.1). Institutional actions refer to measures that can be taken to monitor the plume and reduce potential exposure to the plume. Monitored natural attenuation would take no additional action to control the downgradient plume and would allow the plume to migrate and naturally attenuate through mixing with unimpacted water. Groundwater monitoring would be conducted to confirm that sulfate concentrations are attenuating and existing water supply wells are not impacted. Groundwater control includes technologies that can actively control the extent, movement, and magnitude of the plume. Water treatment refers to technologies that can be used to remove sulfate from water either through treating water in-situ or treating water produced by pumping for groundwater control. Water management actions provide for the use of water produced by mitigation actions.

2.2 Identification and Screening of Control Technologies and Process Options

Control technologies and process options selected as appropriate for each mitigation response action are listed in Table B.1 along with a summary of effectiveness, implementability, and relative cost. The technologies and process options are described below along with the rationale for eliminating some of them from further consideration.

2.2.1 Institutional Actions

Institutional actions are actions that could be employed to reduce or preclude potential exposure to sulfate in the downgradient plume. Groundwater monitoring is the institutional control considered.

2.2.1.1 Groundwater Monitoring

Groundwater monitoring would consist of water quality sampling and analysis, and water level measurement. Groundwater monitoring at monitor and drinking water supply wells would be used as a means of monitoring sulfate concentrations and water level conditions during the mitigation. Additional groundwater monitoring wells would be installed if needed to adequately monitor the downgradient plume. Groundwater monitoring would be used to estimate the attenuation of sulfate and evaluate migration of the plume to verify the performance of the mitigation. Monitoring of drinking water supplies could be used to determine whether a supply is impacted by sulfate from the STI. If a drinking water supply well were to become impacted by sulfate from the STI, drinking water supply mitigation would be implemented in a manner appropriate for the site-specific conditions. Potential drinking water supply mitigation is discussed in Section 2.3.3 of the main text and Appendix C. Groundwater monitoring was retained for use in developing mitigation alternatives.

2.2.2 Monitored Natural Attenuation

The monitored natural attenuation mitigation response action would not actively control the downgradient plume. Water quality monitoring would be conducted to monitor the attenuation of sulfate concentrations and confirm that existing water supply wells would not be impacted. As the plume flows northward it will be diluted by mixing with unimpacted groundwater along its margins and with water recharged to the aquifer through infiltration. The degree of dilution and how long it would take the plume to reach the mitigation level of 250 milligrams per liter (mg/L) sulfate depends on the degree and duration of mixing and the quality of the unimpacted groundwater and recharge.

Water quality monitoring is a key component of monitored natural attenuation. Groundwater monitoring at monitor and water supply wells, and drinking water supply mitigation (Appendix C), if needed, are actions that would be conducted to support monitored natural attenuation. Groundwater monitoring would be conducted to track the movement and attenuation of the plume. Drinking water supplies in the vicinity of the plume would be monitored to evaluate potential impacts. Drinking water supply mitigation would be combined with monitored natural attenuation as a contingency measure should monitoring indicate that a water supply would become impacted. Monitored natural attenuation was retained for mitigation alternative development because it may be effective, it is implementable, and has a relatively low cost.

2.2.3 Groundwater Control

The groundwater control mitigation response action includes technologies that establish hydraulic conditions allowing for the control and removal of sulfate-impacted groundwater for the purpose of controlling plume movement or reducing the sulfate mass in the plume. Two categories of groundwater control technologies are considered for the screening: 1) groundwater pumping and 2) groundwater barriers.

2.2.3.1 Groundwater Pumping

Groundwater pumping technologies use wells to control the migration of sulfate by extracting impacted groundwater. Two general plume management approaches are considered for groundwater pumping: plume stabilization and enhanced mass removal.

Plume stabilization would be achieved by pumping at the leading edge of the plume or other locations at a rate sufficient to minimize or prevent further migration of the downgradient plume. Plume stabilization would require pumping sulfate impacted groundwater at approximately the same rate at which it flows to the leading edge. Because the source control wellfields would be in place, a plume stabilization wellfield would also need to operate until monitored natural attenuation could be implemented. Although plume stabilization can control migration of the downgradient plume, it may take a long time for existing groundwater concentrations in the downgradient plume to decline.

Mass removal is an approach that could be used in conjunction with plume stabilization. As used in this FS, mass removal refers to pumping from locations within the downgradient plume to remove sulfate mass from the plume between the source control wellfields and the downgradient plume margins.

Factors that must be known to design wellfields for plume stabilization or mass removal include 1) the extent of the zone to be managed, 2) the minimum pumping requirements, 3) the number of wells required, and 4) the management of captured water. The number and configuration of wells required for a wellfield, and the need for additional groundwater control actions such as a groundwater barrier or injection wells for efficient capture of groundwater are a function of aquifer conditions at the points of pumping.

For conceptual design purposes it is assumed that sulfate in excess of 250 mg/L is distributed throughout the vertical extent of the basin fill aquifer in the downgradient plume, although detailed designs may incorporate information on the vertical zoning of sulfate at different locations. As described in Section 4.1 of the FS, conceptual designs of wellfields were developed using a numerical model for groundwater flow and sulfate transport to simulate the response of the downgradient plume to various pumping rate and well configurations. The conceptual wellfield designs are described Section 4 of the FS which describes mitigation alternatives. Appendix F describes the numerical model.

The STI and the downgradient plume are within the Tucson Active Management Area. Groundwater pumping for plume management requires a legal right to do so, which is issued by

Arizona Department of Water Resources (ADWR). The FS assumes that groundwater pumping would be conducted pursuant to Sierrita's Type 2 Non-Irrigation Grandfathered Groundwater Right, a Poor Quality Groundwater Withdrawal Permit, or some other right as may be developed in the future.

Groundwater pumping process options considered for this screening are:

- Vertical wells
- Horizontal wells

Potentially applicable process options such as Ranney Wells, shafts, and drifts were not considered because these technologies are inappropriate for plume management given the depth to water (approximately 200 to 400 feet below ground surface), and saturated thickness (500 to 1,000 feet) in the vicinity of the downgradient plume. These process options were evaluated by the FFS (HGC, 2007a) and screened out because depth limitations make them impracticable.

Vertical Wells

This process option would use vertical wells installed to pump from locations at the leading edge of the plume or from within the plume for the purposes of plume stabilization or mass recovery. Wells would be installed to fully penetrate the basin fill. The basin fill in the vicinity of the downgradient plume has a saturated thickness ranging from 500 to 1,000 feet (HGC, 2007b).

The effectiveness of vertical wells should be good and concerns regarding well efficiency are minimized because of the large saturated thickness of the basin fill in the area of the plume.

Wellfields for plume management can be designed and optimized using standard methods such as groundwater flow modeling and analysis of drawdown with analytical equations. The installation and operation of vertical wells is a standard technology that is already used for source control. Thus, the technical implementability of vertical wells is good. This process option will likely require permitting and leasing well sites and easements for the infrastructure needed to establish a wellfield (e.g., pipeline corridor, electrical service, access roads). While large capacity vertical extraction wells are expensive to install and operate, they are expected to be less costly than other potential groundwater pumping options because they are a readily available standard technology. This process option was retained as potentially applicable because of its effectiveness and implementability, although it may have a long lead time for permitting, land access negotiation, and construction.

Horizontal Wells

This process option would pump groundwater from one or more horizontal wells for the purpose of plume stabilization or mass removal. The potential advantages of horizontal wells over vertical wells are screen length and efficiency. A single horizontal well aligned along the axis of the downgradient plume can have a long screen that contacts a larger area of aquifer than a single vertical well. A horizontal well installed at depth in the basin fill may also be more efficient that a vertical well because it would not be susceptible to inefficiency due to drawdown that lowers the saturated thickness over time. Potential disadvantages of horizontal wells are that they are more difficult and expensive to install than vertical wells because they require specialized equipment, crews, and well construction materials that are expensive and less readily available. Horizontal wells may also be more expensive to maintain than vertical wells because they are a non-standard technology. Because of the slope required between the surface penetration of a horizontal well and its target depth, a horizontal well may surface a large distance (thousands of feet) from the zone being pumped. This factor can be an advantage or a disadvantage depending on land access constraints.

Horizontal well technology is used for specialized applications in the petroleum industry. Outside of the petroleum industry, most horizontal wells are installed to shallow depths for remediation purposes rather than water production (Miller, 1996 and Fournier, 2005). Horizontal well technology has been incorporated into environmental remediation applications at some sites with relatively shallow soil and/or groundwater contamination or sites that have unique hydrologic conditions or access restrictions that limit the use of vertical wells. Horizontal wells are not typically used for plume management in hydrologic settings such as the deep basin fill aquifer containing the sulfate plume because conditions generally do not favor selection of the horizontal well technology over vertical wells due to the more difficult implementation and high cost of horizontal wells.

A horizontal well would need to be up to 1,200 feet deep if it is installed to the base of the basin fill. Implementation of a horizontal well would require additional analysis to assess the depth of the basin fill and the number of horizontal wells needed for effective plume management. A contractor specializing in horizontal drilling reported that it would require 2,000 feet of blank casing to reach a depth of 500 feet for screen installation. Although the 500-foot depth of installation was potentially achievable, the contractor indicated that the tracking accuracy decreased with depth and would compromise the ability to install a screen accurately at the base of the basin fill given the irregularities of the basin fill-bedrock contact. Based on this information, the successful installation of a horizontal well to provide effective capture of the downgradient plume is uncertain and the implementability of horizontal well is considered poor.

Horizontal wells are theoretically effective, but they have poor implementability and high cost compared to vertical wells. Horizontal wells provide no advantage over vertical wells in terms of effectiveness of plume management under these site conditions. There is no reason to use a non-standard horizontal well if vertical wells are expected to perform adequately for plume management. For these reasons, horizontal wells were eliminated from further consideration.

2.2.3.2 Groundwater Barriers

Groundwater barrier technologies impede or prevent subsurface flow for the purposes of channeling flow around an area to be isolated, route flow into an area for in-situ treatment, or enhance the performance of groundwater pumping systems. Barriers are a mature remedial technology effective at controlling groundwater flow. Barriers alone cannot be used here for plume management because the plume is too large and deep to isolate within a barrier system. Although ample saturated thickness does not require a barrier for plume management, barriers are evaluated because they can be used in conjunction with extraction wells to increase the effectiveness of wellfields. When used to enhance wellfield performance, barriers are typically placed on the downgradient side of the wellfield where they limit the hydraulic communication between the upgradient and the downgradient aquifers.

Groundwater barriers may be either engineered low permeability structures that are physically emplaced in the subsurface or hydraulic barriers that recharge water to create hydraulic pressure fields that alter groundwater flow patterns. The term hydraulic barrier is used in this FS to denote a process that recharges groundwater to build-up hydraulic head for the purpose of controlling the direction of groundwater flow and enhancing wellfield capture. This process differs from groundwater pumping which depresses the hydraulic head around a wellfield to create a capture zone, although groundwater pumping can also be characterized as a type of hydraulic barrier. In conventional settings, groundwater recharge may be incorporated into an extraction wellfield for several reasons: 1) to create hydraulic head conditions allowing capture of impacted groundwater, 2) to sustain the saturated thickness for pumping efficiency, or 3) to recharge treated water pumped from extraction wells. A hydraulic barrier may be implementable in cases where installation of a physical barrier is not. Also, hydraulic barriers are not permanent because the hydraulic head field dissipates when recharge is stopped.

The three process options considered for groundwater barriers are:

- Physical barriers
- Hydraulic barrier using injection wells
- Hydraulic barrier using infiltration ponds

Physical Barriers

A physical barrier would place a wall of low permeability material in the aquifer downgradient of the wellfield to allow groundwater levels to build up to a point that allows efficient pumping or to channel flow to a point of pumping. Several physical barrier process options are available. Physical barriers, such as slurry walls or funnel and gate systems typically consist of a trench vertically excavated with a backhoe or crane and filled with low permeability material. Barrier materials can be low permeability mixtures of fine-grained soil, clay, and/or cement. Materials such as polyethylene geomembrane sheeting can also be added to barriers to reduce their permeability. Sheet piling can be used in some conditions to create a continuous physical barrier of interlocking steel or plastic panels. Soil mixing and permeation grouting, or jet grouting (grout injection), are additional methods of constructing a physical barrier.

Physical barriers have depth limitations for installation. The practically achievable depth of construction of a physical barrier using excavation is generally less than 150 feet. The depth limitation of sheet piling is shallower than that of excavation. In theory, chemical reagents could be injected at depth into an aquifer to solidify and create a zone of reduced permeability around the injection point, but this is a seldom-used technology with significant uncertainty of effectiveness in the hydrologic setting of the downgradient plume. For these reasons, physical barriers are considered technically infeasible for application at the depths of basin fill in the area of the downgradient plume and were not considered further.

Hydraulic Barrier Using Injection Wells

Injection wells are a commonly used technology for groundwater recharge projects, underground injection of waste, and management of saltwater intrusion. Injection wells could be used to inject water downgradient of an extraction wellfield in order to enhance its effectiveness or attain a larger area of capture. Over time, injection results in a groundwater-mound that increases the local hydraulic head downgradient of the extraction wellfield and flattens or reverses the local hydraulic gradient thereby enhancing the capture of the extraction wells. Using injection wells to create a hydraulic barrier requires a source of injection water that is low in sulfate, meets aquifer water quality standards, and would not plug injection wells. Such a water supply could be obtained from existing water supply wells or by treating water pumped for mitigation.

Although injection wells are a common technology, they can be associated with high capital cost due to the need for pilot testing and high operation and maintenance (O&M) costs due to well clogging and the need for frequent rehabilitation. Clogging can result from chemical precipitates that form when injected water aerates or mixes with subsurface water of a different chemistry, from entrainment of air bubbles that reduce the hydraulic conductivity of the aquifer near the well, or from particulates in the injected water that can clog the well screen, filter pack, and aquifer formation. These potential problems can be minimized by careful design and operation, chemical treatment of water prior to injection to reduce formation of precipitates, and filtration of particulates in injected water (Pyne, 2005).

A hydraulic barrier with injection wells has the potential to be effective, although problems with well clogging and injection efficiency can limit effectiveness if it results in excessive down time. Injection wells can theoretically be used to enhance the performance of a plume management wellfield, but there is no expectation that such enhancement would be needed given the aquifer conditions in the vicinity of the plume. Implementation of a hydraulic barrier with injection wells is technically feasible because the technology is readily available, but design studies and pilot testing would be needed to evaluate clogging issues and injection efficiency. Operation of injection wells would require obtaining a U.S. Environmental

Protection Agency Underground Injection Control (UIC) permit and an Arizona Aquifer Protection Permit (APP). The cost of an injection wellfield would be high compared to an extraction wellfield alone because of the additional cost of obtaining potable water or treating water to a quality suitable for recharge, building pipelines to deliver water to the injection wells, drilling and constructing injection wells, and the high level of O&M required. Injection wells for hydraulic barriers are not considered further because of concern about injection well effectiveness due to potential clogging and O&M requirements, lack of the need to access a potable supply for injection, and the high cost of O&M given the need for a barrier to effectively operate a plume management wellfield.

Hydraulic Barrier Using Infiltration Ponds

Infiltration ponds are a commonly used technology for groundwater recharge. Infiltration ponds would be used to infiltrate water downgradient of an extraction wellfield to enhance the effectiveness of the wellfield. Creation of a hydraulic barrier with infiltration ponds would use surface ponds or an infiltration gallery to infiltrate water to the water table by gravity flow through the vadose zone. A groundwater mound would grow once a continuous zone of recharge is established between the surface and the water table. The groundwater mound would increase the local hydraulic head field and flatten or reverse the local hydraulic gradient, enhancing the effectiveness of the extraction wells.

Infiltration ponds are implementable, but would require land access in the area of the plume. Construction and operation of infiltration ponds would require an APP permit. The effectiveness and implementability of infiltration ponds are dependent on the infiltration capacity at potential recharge sites, the character of subsurface materials, the hydraulic loading required, and land availability. A source of low sulfate water meeting aquifer water quality standards would be required for recharge or water would have to be treated prior to recharge.

The vertical permeability of subsurface materials strongly influences the timing and geometry of groundwater recharge by infiltration. Layers of fine-grained sediment in the vadose zone as observed in the vicinity of the plume (HGC, 2007b) could either impede the vertical migration of infiltration or lead to perched water zones in which recharge water may spread laterally. Thus, compared to well injection, the placement of recharge water by infiltration is expected to be less exact due to site-specific geologic conditions. To be effective for plume management, a hydraulic barrier would need to be designed to deliver water to the subsurface in a specific location and at specific rates. Infiltration ponds are not considered to deliver recharge to the water table precisely enough to allow their use as an effective hydraulic barrier for plume management. Infiltration ponds are potentially implementable but would require costs for land access, pipelines, and water supply development.

Infiltration ponds are rejected as a process option because of their ineffectiveness, the lack of need for a barrier to effectively operate a plume management wellfield, the need to access a potable supply for infiltration, and the need to acquire land for infiltration ponds.

2.2.4 Water Treatment

The water treatment mitigation response action consists of technologies capable of removing sulfate from water by chemical, physical, or biological means. Chemical treatment uses reagents to adjust the chemistry of water to remove sulfate by precipitation or transformation into sulfide. Physical treatment methods remove sulfate from water using semi-permeable membranes as ionic filters. Biological treatment removes sulfate from water using microbial processes for the biological transformation of sulfate to sulfide or elemental sulfur. In the context of this FS, water treatment has two potential applications:

- In-situ treatment would add reagents to the subsurface aquifer to modify the groundwater chemistry in such a way that sulfate in groundwater downgradient of the IW wellfield is either precipitated or reduced to sulfide through chemical or biological processes.
- Ex-situ treatment would use conventional water treatment technologies to remove sulfate from water for discharge, for use under a water management option (Section 2.2.5) or if a groundwater control option requires water for recharge.

2.2.4.1 In-situ Treatment

In-situ treatment technologies manipulate the groundwater chemistry in the subsurface area to be treated through the injection or infiltration of reagents that can lead to the precipitation or transformation of the chemical of concern. For in-situ treatment to be used for plume management, the treatment must be able to directly remove or transform sulfate in the groundwater flow of the downgradient plume. In-situ chemical treatment of sulfate would require injection of reagents either to precipitate sulfate in the subsurface or to induce conditions that could reduce sulfate to sulfide. In-situ biological treatment would inject reagents to enhance the activity of endogenous or exotic microbial populations capable of reducing sulfate to sulfide.

In-situ treatment is typically used to treat groundwater containing organic chemicals, although there are also examples of in-situ treatment of metals. The size of typical applications of in-situ treatment in terms of groundwater flow rates and areal extent is small (i.e., hundreds of gpm or less and tens of acres or less) compared to the size of the groundwater flow system from the north part of the IW wellfield (i.e., thousands of gpm and hundreds of acres). In-situ treatment would require equipment, infrastructure, and reagent supply to provide a uniform and continuous delivery of chemicals to the zone of treatment to treat the sulfate load in the downgradient plume. Pilot testing of in-situ treatment would be needed for selection of reagents, determination of application rates, and hydrologic characterization. UIC and APP permits would be required for in-situ treatment.

In-situ treatment of sulfate by chemical and biological means is theoretically possible, but is not a widely used technology . Although there are cases of in-situ treatment in which sulfate is reduced by precipitation of metal sulfides in the presence of high metals concentrations or is reduced to sulfide in the presence of elevated concentrations of organic compounds, there are few, if any, field demonstrations of the in-situ treatment for sulfate only. Chemical precipitation of sulfate as gypsum, barium sulfate, or metal sulfides would not be practical for in-situ treatment because of the low sulfate removal efficiency (in the case of gypsum), potential clogging of injection wells and the aquifer by precipitates, the need to continuously inject large amounts of reagents into the aquifer, and the difficulty of uniformly delivering chemicals throughout the saturated thickness of the aquifer so that a continuous zone of treatment is created. The use of reducing agents for in-situ chemical or biological reduction of sulfate would be ineffective because sulfide would remain mobile in groundwater in the absence of metals.

Although some sulfide might precipitate as pyrite in the aquifer, most sulfide would either reoxidize to sulfate when mixing with regional groundwater flow or would remain in solution as an undesirable constituent such as hydrogen sulfide.

Given the lack of prior examples of in-situ methods being used to treat sulfate only at the scale and flow rate of the downgradient plume, the current effectiveness of in-situ treatment is uncertain. In-situ treatment is potentially implementable in that technologies are available with which to attempt in-situ treatment of sulfate. However, significant pilot testing would be needed to design an in-situ treatment system and verify its performance. In-situ treatment was rejected as a potentially applicable process option because of its uncertain effectiveness and the need for site-specific pilot testing.

2.2.4.2 Ex-situ Treatment

Ex-situ treatment might be used in the event that sulfate-bearing water pumped for plume management needs treatment, such as in the event that mine use of mitigation water (Section 2.2.5.1) is no longer feasible. Process options for ex-situ treatment of sulfate consist of the standard treatment technologies for sulfate removal, such as chemical precipitation, ion exchange, biological treatment, or membrane processes (reverse osmosis, nanofiltration, or electrodialysis reversal) (Lorax Environmental, 2003). Sulfate removal by membrane process is the predominant sulfate treatment methodology used in practice.

MWH (Appendix D) reviewed potentially applicable technologies for treating sulfate at concentrations and flow rates similar to those that would be needed to treat water from the downgradient plume. The review evaluated sulfate treatment by chemical precipitation, ion exchange, membrane separation, biological treatment, and distillation. Membrane separation was identified as the most economically feasible option for sulfate treatment. Electrodialysis, electrodialysis reversal, and reverse osmosis (RO) were evaluated as potentially applicable membrane separation processes. RO was identified as the most effective sulfate treatment technology. The brine reject from RO treatment is estimated to be approximately 25 percent of the total influent flow. In-pit disposal or enhanced brine evaporation were identified as effective ways to manage the RO reject water. In-pit disposal of RO reject would require pumps and pipelines to convey reject water to the pit and a decision by Sierrita to use the pit for water management (Section 2.2.5.2). Enhanced brine evaporation would require construction and operation of evaporation ponds at Sierrita. In-pit disposal of brine evaporation residuals was identified for managing residuals from brine evaporation. Sulfate treatment using RO is expensive to construct and operate due to equipment costs, power consumption, and the production of a brine reject that needs recycling or disposal. For example, the capital costs for construction of a system capable of treating 2,000 gpm and evaporating the brine reject is approximately $20 million (Appendix D). RO is an implementable and effective ex-situ treatment processes that is retained in the event water treatment is needed, although other emerging technologies (e.g., Lorax Environmental, 2003) may be available for consideration if treatment is ultimately needed.

A.R.S. § 49-286 indicates that blending is a potentially applicable process option for meeting water quality standards. Blending is the process of mixing waters with high and low sulfate concentrations to produce a water meeting the sulfate action level. Blending is commonly practiced in aquifer recharge and storage projects that mix different water types in the subsurface to allow recovery of product water that is of higher quality than the recharge water. Blending was not reviewed by MWH because no specialized treatment technology is required. However, blending may potentially have a role in treatment for future water management and its application would be case-specific. Potential sources of fresh water for blending might be Canoa Ranch wellfield water or treated water. The benefits of blending are its effectiveness at producing potable water, easy implementability, and low cost. Blending was retained as a water treatment process option.

2.2.5 Water Management

Groundwater pumped for plume management would have to be used or stored. Currently groundwater extracted by the IW wellfield is used at the mine. In the event that mine use is no longer feasible, another use for water would be needed or the water would need to be stored and evaporated. Three water management options are screened for potential application.

- Use in mining operations
- In-pit storage
- Treatment for beneficial use

2.2.5.1 Use in Mining Operations

Water pumped from the IW wellfield is currently used as water supply for the Sierrita Mine under Sierrita's Type II rights and permits. The use of water in mining operations provides a beneficial use for sulfate-impacted water and reduces the demand for fresh water from other wellfields. The use of water in mine processes is dependent on the industrial water demand of the mine and the chemistry of the water. Currently, a steady demand for water is expected through the projected end of mine life in 2042. The chemistry of water pumped for plume management is suitable for use in mine processes.

Use of water in mining operations is effective and implementable. The potential to use existing infrastructure and the avoidance of the high cost of water treatment make water use at the mine cost-effective compared to surface discharge or use as drinking water, both of which would require water treatment. Mine use is an effective process option as long as there is an operational water demand. If mitigation pumping is required following the cessation of mining or if the operational water demand decreases below the level of mitigation pumping, other water management process options would need to be implemented consistent with ADWR rights and permits. Use of water in mining operations was retained as a water management process option during mine life.

2.2.5.2 In-Pit Storage

In-pit storage and evaporation would pump mitigation water to the Sierrita pit. This process option would be applicable following cessation of mining in Sierrita pit and would create a pit lake. Water stored in the pit would evaporate.

In-pit storage would be conducted by maintaining the pit as a hydraulic sink so that solutions in the pit do not flow into the surrounding aquifer. A hydraulic sink condition occurs when the water elevation in the pit is less than the water elevation in the surrounding aquifer, thereby creating inward dipping hydraulic gradients that cause groundwater to flow into the pit and do not allow pit lake water to flow into the surrounding aquifer. Hydraulic sink conditions are maintained by managing the water elevation in the pit lake relative to the water elevation in the surrounding aquifer. In-pit storage is feasible provided the inflow rate of mitigation water does not cause too much filling. Thus, the potential applicability of in-pit storage for water management depends on the expected flow rates over time during the mitigation.

In-pit storage would be an effective water management option depending on the magnitude of mitigation flows over time. In-pit storage is implementable with standard pump and pipeline equipment. Sierrita would conduct in-pit water management actions in compliance with applicable groundwater regulations. The cost of in-pit storage would be significantly less than water treatment because it has relatively low infrastructure and operating requirements. In-pit storage is retained for mitigation alternative development.

2.2.5.3 *Treatment for Use*

Water generated by plume management pumping could be treated for use. RO water treatment could be used to meet water quality needs for different potential water uses. Potential uses of treated water include drinking water supply, return to aquifer, or agricultural supply.

Use as drinking water would require water treatment to meet the sulfate mitigation level and applicable drinking water standards. Treated water could be conveyed to public water supply lines and sold to a water company to augment the local water supply and reduce water supply pumping by local water providers. The treatment facility and distribution system to implement this option may need to comply with Arizona regulations regarding public water systems (Arizona Administrative Code R18-4-201 through R18-4-290) depending on the exact circumstances.

Water generated by plume management pumping could potentially be returned to the aquifer using infiltration, injection or other technology. Any action to water management actions to return treated water to the aquifer would comply with applicable environmental and groundwater regulations, including an Arizona Pollutant Discharge Elimination System permit and an APP. Because this process option would return water to the aquifer, treatment of sulfate to a concentration that would not adversely impact groundwater and surface water would be needed. Any action to return treated water to the aquifer would need to be done in such a way that recharge does not add to the volume of the plume.

Plume management water could be treated to a level suitable for agricultural use. The treated water would need to be conveyed to the point(s) of application and sold to an agricultural user to reduce agricultural pumping. Because this process option would return water to the aquifer, treatment of sulfate to a concentration that would not adversely impact crops and groundwater would be needed, and the action would need to be done in such a way that recharge does not add to the volume of the plume.

Treating water for use could be an effective means of water management. This process option is potentially effective, although there may be constraints on certain post-mine end uses of treated water depending on water rights and permits in effect at the time. Water treatment for use is potentially implementable, but certain uses would require the cooperation of other parties and the public. Treatment of water for use would have a high cost for water treatment and, depending on the circumstances, for conveyances to bring water the point of use. The cost of water treatment for water management would be significantly more expensive than mine use and in-pit storage. Water treatment for use was eliminated as a process option due to its high cost compared to mine use or in-pit storage. Water treatment for use would be considered if mine use and in-pit disposal are infeasible.

2.3 Summary of Screening of Mitigation Actions, Technologies, and Process Options

The screening of mitigation actions, technologies, and process options for plume management considered a range of potentially applicable actions for incorporation into mitigation alternatives. The screening process qualitatively narrowed the range of options on the basis of effectiveness and implementability (Table B.1).

Process options retained for plume management are listed below:

- Institutional Actions:
  - Groundwater Monitoring

- Monitored Natural Attenuation

- Groundwater Control:
  - Vertical Wells

- Water Treatment:
  - Ex-Situ Treatment by Reverse Osmosis
  - Blending

- Water Management:
  - Use in mining operations (during mining)
  - In-pit storage (after mine life)
  - Treatment for use (if mine use or in-pit storage are infeasible)

The range of process options retained for plume management in the vicinity of the STI would accommodate a passive approach for plume management, monitored natural attenuation, and active approaches that would use groundwater pumping to control plume migration. The plume management process options retained for alternatives development provide an array of techniques including institutional, water treatment, and water management actions that can be incorporated into mitigation alternatives consistent with Section III.D of the Mitigation Order. Section 3 of the FS describes the application of the retained process options in mitigation alternatives. The results of conceptual design studies and simulation of mitigation alternatives using plume management are discussed in Section 4 of the FS.

3. REFERENCES

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4. LIMITATIONS STATEMENT

The opinions and recommendations presented in this report are based upon the scope of services and information obtained through the performance of the services, as agreed upon by HGC and the party for whom this report was originally prepared. Results of any investigations, tests, or findings presented in this report apply solely to conditions existing at the time HGC's investigative work was performed and are inherently based on and limited to the available data and the extent of the investigation activities. No representation, warranty, or guarantee, express or implied, is intended or given. HGC makes no representation as to the accuracy or completeness of any information provided by other parties not under contract to HGC to the extent that HGC relied upon that information. This report is expressly for the sole and exclusive use of the party for whom this report was originally prepared and for the particular purpose that it was intended. Reuse of this report, or any portion thereof, for other than its intended purpose, or if modified, or if used by third parties, shall be at the sole risk of the user.

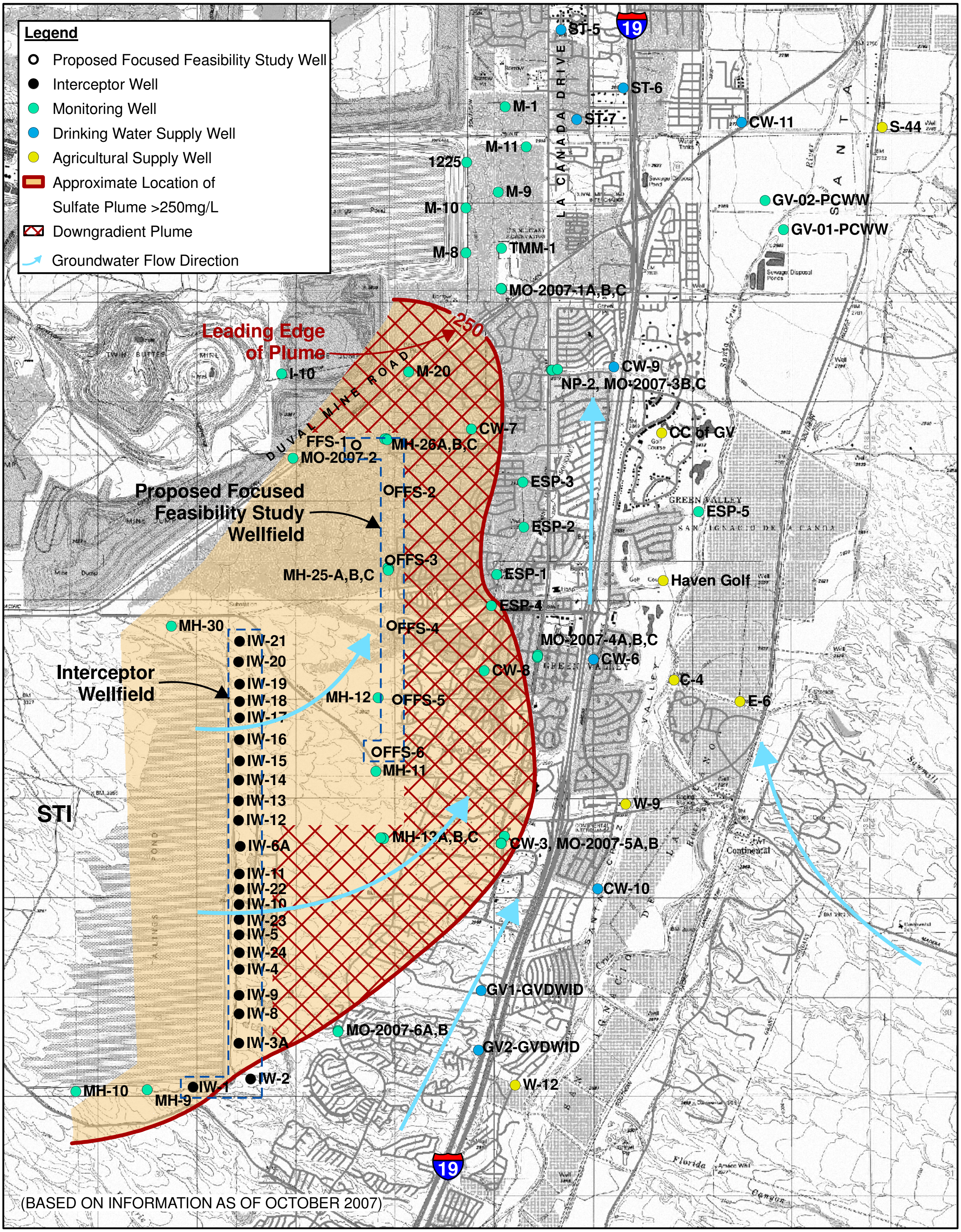
TABLE

TABLE B.1
Screening Evaluation of Mitigation Response Actions, Control Technologies, and Process Options for Plume Management

Mitigation Response Action	Control Technology	Process Option	Effectiveness	Implementability	Cost	Evaluation
PLUME MANAGEMENT						
Institutional Actions	Groundwater Monitoring	Ongoing groundwater monitoring at monitoring and drinking water supply wells	Potentially effective at determining the magnitude and extent of the plume	Implementable; may require installation of additional monitoring wells	Low	Retain for alternative development
Monitored Natural Attenuation	Sulfate Attenuation Through Mixing	Sulfate impacted groundwater mixes with and is diluted by groundwater and recharge waters	Potentially effective depending on how sulfate concentrations naturally attenuate.	Implementable; may require installation of additional monitoring wells	Low	Retain for alternative development
Groundwater Control	Groundwater Pumping	Vertical wells	Potentially effective; standard technology for plume management	Implementable; requires land access and right of way for wells and pipelines	Medium	Retain for alternative development
		Horizontal wells	Potentially effective, but is a non-standard technology	Implementable, but requires specialized equipment, personnel, and well construction materials	High	Rejected because option is a non-standard technology that is more costly than vertical wells
	Groundwater Barriers	Physical barriers	Ineffective for this application; physical barriers are difficult to install to depths greater that 150 feet	Not implementable due to technical infeasibility given site-specific conditions	High	Rejected because option is ineffective and infeasible for plume management
		Hydraulic barrier using injection wells	Potentially effective; a hydraulic barrier can be created by injecting low-sulfate water, but effectiveness is uncertain due to complex O&M; requires pilot testing	Implementable, but technology is associated with a high level of O&M that can impact effectiveness	High	Rejected because option has uncertain effectiveness and because there's no apparent need for a barrier to enhance wellfield performance
		Hydraulic barrier using infiltration	Potentially effective; a hydraulic barrier can be created by infiltration ponds but would take a long time to reach steady state, is difficult to test and control, and may be influenced by perching.	Infiltration gallery is potentially implementable, but requires land for ponds	Medium	Rejected because option is not as effective as injection wells and there's no apparent need for a barrier to enhance wellfield performance
Water Treatment	In-Situ Treatment	Inject reagents for chemical precipitation or chemical or biological reduction of sulfate in the aquifer	Potentially ineffective due to difficulty of attaining uniform treatment and potential well and aquifer clogging, site-specific testing needed to evaluate effectiveness	Site-specific pilot testing needed to evaluate implementability; would require APP and UIC permits	High	Effectiveness and implementability uncertain; not considered further
	Ex-Situ Treatment	Treatment by reverse osmosis	Effective; capable of meeting water quality standards and meeting the 250 mg/L sulfate limit	Implementable; produces a brine reject that requires management	High	Retain for alternative development in the event post-mine life treatment is needed for water management
		Blending	Effective; capable of meeting water quality standards and meeting the 250 mg/L sulfate limit	Implementable; requires source of water for blending	Medium	Retain for alternative development in the event post-mine life treatment is needed for water management
Water Management	Mine Use	Pump water to mine for use without treatment	Effective; dependant on water need in the mining operation; current projected mine life is through 2042	Implementable; currently in practice	Medium	Retain for alternative development
	In-Pit Storage	Water storage and evaporation in Sierrita pit	Effective; water storage can effectively manage mitigation water provided that the flow rate allows maintenance of hydraulic sink conditions	Implementable; would need to comply with applicable regulations	Medium	Retain for alternative development if mine use is infeasible
	Treatment for Use	Water treatment to meet standards appropriate for use (e.g., drinking water supply, release to aquifer, agricultural supply)	Effective; water treatment can effectively reduce sulfate concentrations to levels appropriate for potential uses	Implementable, but not preferred compared to mine use and in-pit storage due to significantly higher cost of treatment and conveyance; certain end uses may be limited by rights and permits in effect at the time	High	Retain for alternative development if mine use and in-pit storage are infeasible

Shading indicates option retained for alternative development

FIGURE



0 2,500 5,000 Feet

PROJECTION:
UTM Zone 12N NAD83

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HYDRO GEO CHEM, INC.

LOCATION OF THE DOWNGRADIENT SULFATE PLUME AND SOURCE CONTROL WELLFIELDS

Approved	Date	Author	Date	File Name	Figure
JRN	09/12/08	RAM	09/12/08	78307001 2G	B.1