WORK PLAN TO CHARACTERIZE AND MITIGATE SULFATE WITH RESPECT TO DRINKING WATER SUPPLIES IN THE VICINITY OF THE PHELPS DODGE SIERRITA TAILING IMPOUNDMENT, PIMA COUNTY, ARIZONA

Prepared for:

PHELPS DODGE SIERRITA, INC.
6200 West Duval Mine Road
Green Valley, Arizona

Prepared by:

HYDRO GEO CHEM, INC.
51 West Wetmore Road, Suite 101
Tucson, Arizona 85705
(520) 293-1500

August 11, 2006

HYDRO GEO CHEM, INC.
Environmental Science & Technology

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6200 West Duval Mine Road
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Prepared by:

HYDRO GEO CHEM, INC.
51 West Wetmore Road
Tucson, Arizona 85705
(520) 293-1500

Approved by:

James

30842
JAMES R.
NORRIS
8/11/06

James R. Norris
Arizona Registered Geologist No. 30842

August 11, 2006

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LIST OF ACRONYMS

A.A.C.	Arizona Administrative Code
ACP	Aquifer Characterization Plan
ADEQ	Arizona Department of Environmental Quality
ADWR	Arizona Department of Water Resources
A.R.S.	Arizona Revised Statutes
ASLD	Arizona State Land Department
AWQS	Aquifer Water Quality Standards
BESST	BESST, Inc.
CWC	Community Water Company
DQO	Data Quality Objective
FS	Feasibility Study
GIS	Geographic Information System
MCL	Maximum Contaminant Level
MO	Mitigation Order
PAG	Pima Association of Governments
PDSI	Phelps Dodge Sierrita, Inc.
PDSTI	Phelps Dodge Sierrita Tailing Impoundment
QAPP	Quality Assurance Project Plan
SDP	Sewage Disposal Ponds
TDS	Total Dissolved Solids
UTM	Universal Transverse Mercator

1. INTRODUCTION

A plume of sulfate-bearing groundwater has been detected downgradient of the Phelps Dodge Sierrita Tailing Impoundment (PDSTI) south of Tucson, Arizona (Figures 1 and 2). In June 2006, Arizona Department of Environmental Quality (ADEQ) and Phelps Dodge Sierrita, Inc. (PDSI) entered into a Mitigation Order on Consent (Docket No. P-50-06) (MO) requiring PDSI to characterize the extent of sulfate in groundwater and to develop a Mitigation Plan for any impacted drinking water supplies attributable to the PDSTI.

PDSI is now mitigating sulfate through groundwater pumping and providing alternative water supplies. The MO provides a structure for conducting additional environmental investigations and evaluating additional potential mitigation alternatives. As a requirement of the MO, this work plan presents the rationale and methods for further investigation and development of a Mitigation Plan. Hydro Geo Chem, Inc. prepared this work plan on behalf of PDSI.

1.1 Mitigation Order Requirements Pertaining to Work Plan

Section III.A of the MO requires a work plan designed to complete characterization of the vertical and horizontal extent of the sulfate plume downgradient of the PDSTI. Specific work identified in the MO includes:

- A summary of existing information on the characterization of the sulfate plume downgradient of the PDSTI, including references to known and ongoing characterization and assessment information (MO Section III.A.1),

- A Quality Assurance Project Plan (QAPP), with a schedule of implementation, that defines the sulfate plume characterization and assessment objectives, and describes the methods, organization, analyses, and Quality Assurance and Quality Control that PDSI will implement and/or perform to ensure that characterization and assessment objectives are met (MO Section III.A.2),

- A plan encompassing one or more phases, to complete characterization of the sulfate plume downgradient of the PDSTI with an implementation schedule that includes site access and permitting requirements. The plan is to include sampling and testing of additional monitoring wells necessary (1) to identify the horizontal and vertical extent of the sulfate plume downgradient of the PDSTI as defined by concentrations in excess of 250 milligrams per liter (mg/L), and (2) to evaluate the fate and transport of sulfate downgradient of the PDSTI (MO Section III.A.3), and

- A plan to inventory all existing registered private wells used as a drinking water source or public drinking water system wells located within a (1) mile radius of the sulfate plume's down and cross-gradient outer edge (MO Section III.A.4).

In accordance with Section III.C of the MO, the findings of this work are to be reported in an "Aquifer Characterization Report". In addition to the work identified in Section III.A of the MO, Section III.C.4 requires the Aquifer Characterization Report to address the effectiveness of the existing sulfate control system.

Section III.D of the MO requires a Mitigation Plan that identifies and evaluates alternatives that practically and cost effectively provide drinking water meeting applicable sulfate levels to the owner or operator of an impacted drinking water supply in accordance with Arizona Revised Statute (A.R.S.) § 49-286. An impacted drinking water supply is one that is determined to have an average sulfate concentration in excess of 250 mg/L due to sulfate from the PDSTI. The Mitigation Plan is to include sampling and analysis methods for documenting the average sulfate concentration of a drinking water source, and a process for verifying that the sulfate is due to the PDSTI.

Although sulfate is a non-hazardous constituent and the applicable legal criteria to address the plume are set forth in the MO and A.R.S. § 49-286, the process approach outlined in the MO and incorporated in this work plan generally is modeled after the process for remedial investigations and feasibility studies used in the Arizona Water Quality Assurance Revolving Fund and the Federal Superfund Program. This work plan proposes an Aquifer Characterization Plan (ACP) and a Feasibility Study (FS) for sulfate mitigation to address the requirements of the MO. The ACP will determine the nature, extent, fate, and transport of sulfate and will gather information needed to develop mitigation action alternatives consistent with the MO. The FS will identify and evaluate mitigation action alternatives and recommend a Mitigation Plan in accordance with the objectives in the MO.

Although not addressed by this work plan, the MO also requires:

- the formation of a community advisory group which will meet four times yearly,
- a local information repository for the dissemination of information about the MO, and
- submittal of quarterly status reports to ADEQ.

1.2 Work Plan Organization

The components of this work plan are meant to fulfill the work requirements in Sections III.A, III.C, and III.D of the MO. The work plan is organized as follows:

- **Section 1- Introduction.**
- **Section 2 - Summary of Existing Information**. Section 2 discusses background information, describes the current efforts to mitigate sulfate, and presents an overview of the geology, groundwater hydrology, and water quality including the known occurrence and extent of sulfate downgradient of the PDSTI.
- **Section 3 - Aquifer Characterization Plan**. Section 3 describes work to further characterize the nature and extent of sulfate in groundwater. This work will include: a well inventory to identify private drinking water wells and public water supply systems located downgradient and cross-gradient of the sulfate plume; groundwater monitoring; monitoring well installation and testing to determine the aquifer structure, to further delineate the extent of sulfate, and to quantify aquifer hydraulic properties; an analysis of the effectiveness of the current mitigation control strategy; numerical modeling of groundwater flow to predict the future movement of sulfate and to test potential control strategies; and reporting.
- **Section 4 – Identification of Potential Interim Actions.** Work to identify potential interim actions is described in Section 4. This task which is consistent with FS activities, considers potential interim actions if average sulfate concentrations exceed 250 mg/L in a drinking water supply before the Mitigation Plan is completed.
- **Section 5 - Feasibility Study for Sulfate Mitigation Plan**. Section 5 provides the work plan for an FS to develop a sulfate Mitigation Plan. The FS will identify mitigation action objectives, evaluate potentially applicable response actions and technologies, identify mitigation alternatives for meeting the project objectives, evaluate the benefits and costs of the alternatives, and produce a Mitigation Plan.
- **Section 6 - Schedule.** The work and reporting schedule for the ACP and FS for the Mitigation Plan is provided in Section 6. The ACP and FS have been designed to proceed in parallel to identify mitigation options early in the process. Tasks related to identifying and addressing potentially impacted drinking water supplies (e.g., well inventory and identification of potential interim actions) are scheduled to be completed as soon as possible in the process.

The appendices provide various supporting materials referenced in the text including a QAPP describing the work methods to be used.

2. SUMMARY OF EXISTING INFORMATION

Section III.A.1 of the MO requires a summary of existing information on the extent of sulfate in groundwater downgradient of the PDSTI, including references to known and ongoing characterization and assessment information. To address this requirement, this section provides an overview of the estimated extent of sulfate in groundwater; reviews the current mitigation actions being taken by PDSI to address sulfate; describes the geology, groundwater hydrology, and water quality downgradient of the PDSTI; and presents a conceptual model of the sulfate plume.

2.1 Background

The PDSTI is approximately 25 miles south of Tucson and from 0.5 to 1.5 miles west of Green Valley in Pima County, Arizona (Figures 1 and 2). The PDSTI covers approximately 3,600 acres located east of the Phelps Dodge Sierrita Mine open pit and mineral processing operations, and west of Green Valley.

The PDSTI is one of several tailing impoundments associated with mines in the Pima mining district. Immediately north of the PDSTI is the inactive Twin Buttes Mine. The Pima mining district had sporadic mining activity starting in the late 1800s, but large-scale development of the copper and molybdenum deposits using modern mining methods did not begin until the 1950s.

In the 1970s, groundwater was found to contain elevated concentrations of sulfate in the vicinity of PDSTI and other mines in the Pima mining district (Pima Association of Governments (PAG), 1983a and 1983b). The origin of the sulfate was identified as seepage from various tailing impoundments into the underlying aquifers.

Tailing impoundments contain the finely milled rock resulting from the liberation of ore minerals at the mines. Tailing are deposited as a slurry containing a high percentage of water. As the solids settle out of the slurry to form the impoundment, tailing water collects in ponds on top of the tailing. Although much of the water contained in tailing evaporates or is reclaimed by pumping it to the mine for reuse, some portion of the water infiltrates the subsurface below the impoundments and mixes with the ambient groundwater flow system. The sulfate concentration of the seepage depends on the original sulfate concentration in the slurry, any concentration by evaporation or dilution by admixture with precipitation or other waters added to the impoundment, and any sulfate produced by oxidation of residual sulfides in the tailing. The sulfate concentration in groundwater flowing in the vicinity of the tailing impoundment depends on the relative volumes and concentrations of sulfate in the tailing seepage and the groundwater into which it mixes.

The MO sets an average sulfate concentration of 250 mg/L for drinking water supplies. As illustrated in Figure 3, groundwater sampling conducted in the Green Valley area has identified a groundwater plume with sulfate concentrations in excess of 250 mg/L based on data available as of April 2006. The zone of elevated sulfate extends from the base of the PDSTI northeast to the western edge of Green Valley and north to approximately Duval Mine Road. As discussed in Section 2.5.1.5, the northern-most extent of the plume is inferred based on apparent historic migration rates. In April 2006, concentrations of sulfate in wells near the eastern edge of the tailing impoundment ranged from 100 to 1,750 mg/L. Based on available data between December 2004 and April 2006, concentrations in wells on the west side of Green Valley ranged from approximately 20 to 570 mg/L.

Because sulfate concentrations exceeding 250 mg/L have been detected in two Community Water Company (CWC) drinking water supply wells, ADEQ determined that a drinking water source is being or is about to be rendered unusable without treatment under A.R.S. § 49-286. In June 2006, PDSI and ADEQ entered into the MO to address the sulfate attributable to the PDSTI.

The MO requires PDSI to mitigate an impacted drinking water supply if the supply can be verified as having an average sulfate concentration greater than 250 mg/L as a result of the sulfate plume originating from the PDSTI. As stated in Section II.B.4 of the MO and A.R.S. § 49-286, mitigation measures may include:

- Providing an alternate drinking water supply.
- Mixing or blending if economically practicable.
- Economically and technically practicable treatment prior to ingestion.
- Other mutually agreeable mitigation measures.

2.2 Current Sulfate Mitigation Actions

Current PDSI *mitigation actions consist of:*

- groundwater pumping to control the migration of sulfate-bearing water in the aquifer,
- alternative water supplies, and
- groundwater monitoring.

PDSI has installed and operates groundwater pumping wells along the eastern and southeastern boundaries of the PDSTI to intercept sulfate-bearing groundwater before it can flow eastward and mix with groundwater in the regional flow system. These wells are called the "interceptor wellfield". Water from this wellfield is pumped for reuse at the mine.

The first eleven interceptor wells (IW-series wells in Figure 3) were installed between 1978 and 1984. Since 1984 the wellfield has been expanded by the installation of new wells and replacement of damaged wells. In April 2006, the interceptor wellfield pumped approximately 5,550 gallons per minute (gpm) from 23 wells that are designed to be pumped continuously. Since 2002, PDSI has expanded the capacity of the interceptor wellfield through a program of well rehabilitation, well replacement, and infrastructure improvements. The current wellfield pumping rate is approximately 24 percent greater than the 2002 average annual extraction rate of 4,485 gpm.

PDSI is working with CWC to develop both an interim and permanent alternative water supply for the two CWC wells showing elevated sulfate. In June 2005, CWC suspended use of drinking water supply wells CW-7 and CW-8 (Figure 3) due to sulfate concentrations. As an interim alternative drinking water supply, PDSI is providing CWC with water from three PDSI wells known as ESP-1, ESP-2, and ESP-3. PDSI is working with CWC to develop a permanent replacement drinking water supply consisting of two new wells, CW-10 and CW-11 (previously known as AN-1). Because these two new wells contained elevated levels of arsenic attributable to natural background conditions, PDSI has agreed to provide arsenic treatment systems to meet drinking water standards at the wells.

Monitoring well installation, water level monitoring, and groundwater sampling are conducted by PDSI to track the amount and extent of sulfate concentrations in groundwater and to evaluate the performance of the interceptor wellfield. Since December 2003, PDSI has installed 10 monitoring wells (MH-13 A, B, C; MH-25 A, B, C/D; MH-26 A, B, C; and MH-30 on Figure 3) to further characterize the sulfate plume. The environmental monitoring and sampling data provide critical information on the nature and extent of sulfate and the dynamics of the groundwater flow system.

2.3 Geologic Setting

This section provides an overview of the geology in the vicinity of the PDSTI. A more detailed description of the geologic units, with reference to characteristics reported in geologic logs for area borings, is provided in Appendix A. Appendix A also contains geologic cross sections through the area of the plume, illustrating the distribution of subsurface materials and other features such as the depth of bedrock and well construction. Geologic data have been drawn from a variety of sources including U.S. Geological Survey publications; reports on various geologic, water supply, and environmental investigations; and a review of geologic logs for area wells.

The PDSTI is in the southern portion of the Tucson basin (Figure 4). The southern portion of the basin is bounded by the Sierrita Mountains on the west and the Santa Rita Mountains to the east, with the axis of the basin lying approximately along the Santa Cruz River. The mountains are composed of bedrock materials, and the basin consists of clastic sediments with some interbedded volcanic rocks. The basin fill deposits are thickest in the center of the basin and thin towards the basin margins.

The geologic units in the PDSTI area can be divided into three generalized units: Recent alluvium, Quaternary and Tertiary basin fill deposits, and the bedrock complex. As discussed in Section 2.4, Recent alluvium is not a significant aquifer because it is typically unsaturated.

Basin fill materials form the primary water supply aquifer in the area. Bedrock is typically a low permeability material that is not a significant aquifer.

Figure 5 is a generalized geologic map taken from Davidson (1973), who characterized the lithology and formations of the basin fill throughout the Tucson basin. Detailed geologic maps of the Sierrita Mountains and Santa Rita Mountains are provided by Cooper (1973) and Drewes (1971a, 1971b), respectively. General descriptions of the geologic units in the vicinity of the sulfate plume are provided in Sections 2.3.1 through 2.3.3.

2.3.1 Recent Alluvium

Recent alluvium consists of the unconsolidated sediment in stream channels of the Santa Cruz River and the various washes that feed into the Santa Cruz River from the surrounding uplands, alluvial fans, and sheet wash deposits (Anderson, 1987). The alluvium is up to approximately 200 feet thick in the vicinity of the Santa Cruz River and includes coarse grained sediments in the stream channel and clayey to sandy overbank deposits on the flood plain of the river (PAG, 1983a). The alluvium is thin in washes tributary to, but distant from, the Santa Cruz River. Geologic logs for monitoring wells completed in stream channel deposits six or more miles west of the Santa Cruz River indicate the alluvium ranges from zero to several tens of feet thick (Errol L. Montgomery & Associates (ELMA), 2001).

2.3.2 Basin Fill Deposits

The Quaternary-Tertiary basin fill is composed of interbedded sequences of sand, gravel, silt, and clay. The basin fill is an important unit because it is the principal aquifer of the region and because it contains the sulfate plume. Sand and gravel are the primary components of the basin fill and dominate the lower portion of the sequence near the PDSTI. Coarse, cobbly horizons and caliche-cemented zones are sometimes present over large areas. Volcanic flows and tuffs occur in the mid-Tertiary portions of the basin fill.

Davidson (1973) differentiated basin fill deposits into three units: the Pleistocene Fort Lowell Formation, the Miocene Tinaja beds, and the Oligocene Pantano Formation. Although Davidson (1973) and Schmidt (PAG, 1983b) projected these units into the Green Valley area, the basin fill is typically undivided in drill logs and other geologic descriptions of the Green Valley area. An exception is the Pantano Formation which is sometimes identified in geologic logs and area descriptions in the Green Valley area (e.g., Errol L. Montgomery & Associates and Dames and Moore (ELMA & DM), 1994; ELMA, 2001).

2.3.2.1 Fort Lowell Formation

The Fort Lowell Formation is composed of locally-derived sediment and is generally coarser grained than the underlying Tinaja beds. The Fort Lowell Formation is coarser at the basin margins and finer toward the center of the basin. The Fort Lowell Formation typically contains 25 to 60 percent material that is coarser than sand; is loosely consolidated to weakly cemented and light brown, gray brown or reddish brown in color; and commonly contains clasts of volcanic rocks in the vicinity of the Sierrita Mountains (Davidson, 1973). The Fort Lowell Formation is estimated to be 200 feet thick in the vicinity of the Twin Buttes Mine tailing impoundments and over 200 feet thick at the south end of the PDSTI (PAG, 1983b).

2.3.2.2 Tinaja Beds

The Tinaja beds are sandy gravels with interbedded conglomerate and sandstone near the margins of the basin, grading to gypsifeous clayey silt and mudstone in the center of the basin. Felsic to mafic volcanic interbeds are locally present. Interpreted as sedimentary detritus filling the basin during subsidence (Davidson, 1973), the Tinaja beds lie unconformably over the Pantano Formation and are overlain unconformably by Fort Lowell Formation. The lower stratigraphic portion of the Tinaja beds outcrop south of Tinaja Wash in the Sierrita Mountains approximately two miles southwest of the PDSTI. There, the Tinaja beds consist of tuffaceous gravel underlain by felsic flows and tuffs with interbedded conglomerate and gravel. Although shown separately, Davidson (1973) and Anderson (1987) consider the mid-Tertiary volcanics shown on the geologic map (Figure 5) to be part of the Tinaja beds.

In the vicinity of the PDSTI, the Tinaja beds are composed largely of sand and gravel due to the close proximity to the basin margin. Also, the clay and evaporate-rich sequence of the Tinaja is absent in this area. Gravel and sand facies occur near the basin margins with 20 to 50 percent of material being coarser than sand in the gravel facies and 5 to 20 percent of material being coarser than sand in the sand facies. Volcanic clasts compose 50 percent or more of the coarse material.

As interpreted by PAG (1983a), the Tinaja beds west of the Santa Cruz River have a maximum thickness of about 300 feet, whereas the thickness of the beds on the east side of the river is about 1200 feet due to faulting. The Tinaja beds are interpreted to be about 125 feet thick east of the Twin Buttes Mine tailing impoundment and 200 feet thick at the southern end of the PDSTI (PAG, 1983b).

2.3.2.3 Pantano Formation

The Oligocene Pantano Formation is a reddish brown, weakly to moderately consolidated sequence described as silty sandy conglomerate, silty and pebbly sandstones, and moderately well cemented gravel. It is composed of granitic, sedimentary and volcanic clasts in an arkosic to clay-rich, sandy matrix and is weakly to strongly cemented by calcium carbonate. The Pantano Formation averages about 50 percent sand and gravel, but ranges from a low of 30 percent to a high of 70 percent sand and gravel (Davidson, 1973). Interbedded volcanic flows are locally present in the sedimentary sequence.

The Pantano Formation is correlative with the Helmet Fanglomerate, which outcrops northwest of the Twin Buttes Mine (Figure 5). The Pantano Formation is believed to be very thin or nonexistent in the vicinity of the Twin Buttes Mine and PDSTI based on drilling at the interceptor wellfield and elsewhere (Montgomery Watson, and Errol L. Montgomery and Associates, 1998, Barter & Kelly 1982, and ELMA 1986, 1989, 1991, 1995, and 2004a). This interpretation was used to develop the geologic cross sections described in Appendix A.

2.3.3 Bedrock Complex

In the PDSTI area, bedrock comprises upper Cretaceous Demetrie Volcanics, lower Cretaceous Angelica Arkose, and Paleozoic limestones. At the Twin Buttes Mine, subsurface bedrock units include Paleozoic and Mesozoic sediments, early Tertiary intrusives, and Precambrian granite (Cooper, 1973, Barter and Kelly, 1982). The bedrock units are generally low permeability, highly indurated materials. An exception to this general condition is a portion of the Demetrie Volcanics underlying the southeast corner of the PDSTI where many of the wells in the south half of the interceptor wellfield intersect, and produce water from, the upper portion of the Demetrie Volcanics. Appendix A discusses the Demetrie Volcanics and other bedrock units in greater detail.

2.4 Groundwater Hydrology

The hydrology of the PDSTI area and Green Valley is discussed by Davidson (1973), PAG (1983a and 1983b), ELMA & DM (1994), and ELMA (2001).

2.4.1 Hydrostratigraphic Units

Groundwater occurs in three hydrostratigraphic units: Recent alluvium, basin fill, and bedrock complex.

2.4.1.1 Recent Alluvium

The Recent alluvium is typically unsaturated. Alluvium along the Santa Cruz River receives recharge from ephemeral surface water flow. Although there may be local perched zones associated with surface water recharge, zones of extensive saturation in the alluvium have not been reported. Monitoring at wells in alluvium filling ephemeral stream channels west of the PDSTI indicates the alluvium is typically unsaturated, although saturated zones up to five feet thick are observed in some wells (ELMA, 2001). The alluvium is not a significant source of water to area wells.

2.4.1.2 Basin Fill

The principal aquifer in the area is hosted by the basin fill. As used in this work plan, the basin fill is considered to be equivalent to the Fort Lowell Formation, Tinaja beds, and Pantano Formation as defined by Davidson (1973). The basin fill is the primary source of water to large production wells in the area due to its large saturated thickness and relatively high permeability.

The saturated thickness of the basin fill in the vicinity of the PDSTI increases from zero at the basin margins, where the water table is in the underlying bedrock, to 600 to 1,000 feet in the more central part of the basin near Green Valley (see water levels posted on cross sections in Appendices A and D). Greater saturated thicknesses probably occur east of Green Valley as the bedrock elevation continues to decline (ELMA & DM, 1994).

Davidson (1973) reports hydraulic conductivities in the general range of 20 to 93 feet per day (ft/day) for Fort Lowell Formation, 1.3 to 54 ft/day for the Tinaja beds, and 0.7 to 13 ft/day for Pantano Formation. Most hydraulic conductivity estimates in the area of the PDSTI are based on wells with screened intervals extending over the entire basin fill thickness. Thus, the estimates represent an average hydraulic conductivity over the thickness of the various basin fill units penetrated by the wells.

2.4.1.3 Bedrock Complex

The bedrock complex is the informal name given to the highly indurated igneous and sedimentary rocks that underlie the basin fill. The permeability of the bedrock complex is mainly fracture controlled and is generally low, with hydraulic conductivities typically less than 0.1 ft/day. The permeability of bedrock materials may be higher where weathered, highly fractured, or interbedded with more permeable strata. For example, the Demetrie Volcanics in the southern part of the interceptor wellfield contain a thick section of permeable bedrock penetrated by many of the pumping wells (Figure A.4a in Appendix A).

2.4.2 Hydraulic Properties

Numerous hydraulic tests have been conducted at wells and borings that penetrate bedrock and basin fill in the vicinity of the PDSTI and within the basin fill to the east and north of the PDSTI. Tests include pumping and slug tests in wells and constant pressure packer tests in bedrock borings. Table 1 summarizes the available hydraulic conductivity test results. Appendix B lists available hydraulic conductivity data.

Based on the data in Table 1, hydraulic conductivity estimates for different bedrock materials range from approximately 0.000007 ft/day to 2.2 ft/day and have geometric means between 0.0047 and 0.12 ft/day. Hydraulic conductivity estimates of the basin fill range from approximately 6.3 ft/day to 100 ft/day in the vicinity of the interceptor wellfield at the downgradient edge of the PDSTI (Appendix B). Between the PDSTI and the more central portions of the basin, hydraulic conductivity estimates range from approximately 4.8 ft/day to 99 ft/day (Appendix B). Estimates from deep production wells screened over large thicknesses of basin fill may be affected by their penetration of deeper, lower permeability materials such as moderately indurated portions of the Pantano Formation. Spinner logging of some of the existing production wells and hydraulic testing of recently installed well nests indicate that the hydraulic conductivity of the basin fill sometimes varies substantially with depth.

Spinner logging conducted in the vicinity of the interceptor wellfield at IW-4, IW-5, IW-9, and IW-12 (ELMA, 2006) indicates the shallow portion of the basin fill aquifer is more productive than the deeper portions, which include Demetrie Volcanics at IW-4, IW-5, and IW-9 in the southern portion of the wellfield and Pantano Formation at IW-12 (Figures A.4a and A.4b in Appendix A). Spinner logging of ESP-4 (ELMA, 2004b), located near the center of the basin, indicates a highly productive zone in the lower portion of the basin fill, approximately 300 to 480 feet below the water table, that is more than twice as productive as either the 300-foot interval above or the 170-foot interval below.

Figure A.5 in Appendix A is a cross-section showing the distribution of hydraulic conductivities in recently installed well nests MH-13, MH-25, and MH-26 east of the interceptor wellfield (Appendix B). Pumping test results at MH-13 indicate that the hydraulic conductivity of basin fill at shallow and intermediate depths ranges from 13.4 to 17.4 ft/d. These hydraulic conductivities are nearly three orders of magnitude higher than the hydraulic conductivity of 0.023 ft/d measured in the deeper basin fill at MH-13. The deeper basin fill at MH-13 is interpreted to be Pantano Formation equivalent. In contrast to the observations at MH-13, testing at the recently installed MH-25 and MH-26 well nests does not show a significant variation in basin fill hydraulic conductivity with depth (Appendix B). Hydraulic conductivities for the shallow, intermediate, and deep screens in basin fill at MH-25 and MH-26 ranged from 41.4 to 54 ft/d and 41.4 to 65.5 ft/d respectively. The Angelica Arkose bedrock at MH-25 has a hydraulic conductivity of 0.067 ft/d, almost three orders of magnitude lower than the overlying basin fill. Based on these data, there is an apparent increase in hydraulic conductivity from MH-13 in the south to MH-25 and MH-26 in the north. Pumping test results at MH-13, MH-25, and MH-26 also indicate the basin fill is anisotropic with estimates of the ratio of horizontal to vertical hydraulic conductivity ranging from 20 to 435.

2.4.3 Potentiometric Relationships

Regionally, groundwater flow in the southern portion of the Tucson basin is generally to the north, roughly in the direction of flow in the ephemeral Santa Cruz River. Sources of water to the basin include surface water recharge of ephemeral streamflow related to precipitation events, underflow from bedrock bounding the basin on the east and west, and recharge from surface impoundments and irrigation projects. Figure 4 illustrates regional potentiometric relationships in the area using Arizona Department of Water Resources (ADWR) water level data for 1994.

Data presented in ELMA (2001) indicate that the hydraulic gradient within the bedrock complex west of the PDSTI is typically eastward, roughly in the direction of the dip of the topographic surface. The eastward flow in the bedrock complex indicates that it is a source of recharge to the basin fill. ELMA (2001) indicates that the potentiometric surface passes continuously from the bedrock to the basin fill beneath the PDSTI. The hydraulic gradient within the basin fill beneath the PDSTI is also primarily eastward, indicating easterly groundwater flow.

East of the PDSTI, the hydraulic gradient changes from primarily eastward, to northeastward, then to primarily northward near the center of the basin. The northward gradient near the center of the basin is generally in the direction of flow of the ephemeral Santa Cruz River. Consequently, the direction of groundwater flow also changes from eastward beneath the tailing impoundment to northward near the center of the basin. These relationships are illustrated in Figure 6, which is a contour map showing recent water levels in the basin fill aquifer.

Based on the data shown in Figure 6, hydraulic gradients immediately downgradient of the PDSTI range from approximately 0.0063 ft/ft to 0.0240 ft/ft in a northeasterly direction. Near the center of the basin (near Highway I-19), hydraulic gradients range from approximately 0.0068 ft/ft to 0.0180 ft/ft in a northerly direction. Hydraulic gradients in the vicinity of active production wells can be strongly affected by groundwater pumping.

Vertical hydraulic gradients, which can result in a vertical component of groundwater flow, are known to exist within the basin fill aquifer based on water level measurements in well nests and on spinner logging of wells in the basin fill aquifer. Vertical hydraulic gradients within the basin fill can be either upward, downward, or negligible depending on pumping conditions, recharge, and the presence of any low permeability semi-confined horizons that may exist. Both upward and downward hydraulic gradients are indicated by vertical flow measurements at the interceptor wellfield. For example, during spinner logging tests under non-pumping conditions, upward flow, indicating an upward hydraulic gradient, was measured in portions of IW-9 and

IW-12; whereas downward flow, indicating a downward hydraulic gradient, was measured in portions of IW-4 and IW-5 (ELMA, 2006). There were also sections of IW-4, IW-5, IW-9, and IW-12 that had no detectable vertical flow indicated a negligible vertical hydraulic gradient. Measured vertical flows were low, typically less than 10 gpm, and ranged from approximately 0.5 to 15 gpm.

Water levels in the basin vary with time based on the relative strength of recharge sources (such as precipitation and infiltration of surface water runoff) and sinks (such as groundwater pumping). Figure 7 shows water elevation hydrographs of wells MH-11, MH-12, and MH-13 from 1985 through early 2006. Over that period, water levels rose through the late 1980s, declined in the early 1990s, rose again in 1993, and have apparently declined since then. The increases in water levels at the beginning of the record, and after 1993, were most likely related to increased precipitation and recharge during 1983 and 1993. The water levels in MH-11, MH-12, and MH-13 are now approximately 20 feet lower than they were in 1985.

2.4.4 Groundwater Flow

Apparent groundwater flow velocities were estimated using available hydraulic property estimates, an effective porosity of 0.25, and recent water level data (Figure 6). The pore velocity, which is equivalent to the rate of movement of a conservative solute, ranges from approximately 171 ft/yr to 653 ft/yr at the eastern edge of the tailing impoundment, and from approximately 197 ft/yr (between S-1 and GV-1) to 657 ft/yr (between ESP-4 and ESP-3) in the more central portion of the basin. The range of calculated pore velocities is due to the variation of the estimated hydraulic gradient and hydraulic conductivity between different locations.

2.5 Water Quality

This water quality review discusses sulfate concentrations in the vicinity of the PDSTI and reviews the chemistry of sulfate-bearing groundwater in the context of overall groundwater quality in the area. This section begins by examining the spatial and temporal distribution of sulfate in groundwater, using both historical and recent data. Next, the general water quality in the area is discussed, focusing on cation-anion composition. Finally, the data are examined for metals that may be associated with sulfate-bearing groundwater.

The water quality data presented by this review are primarily from the groundwater monitoring conducted by PDSI. The data for wells in the vicinity of the PDSTI were compiled through April 2006 and evaluated to develop maps, graphs, and tables for this section. Water quality data for the CW- and ESP-series wells were provided by CWC. Pima County Wastewater also provided data for monitoring wells north of the sewage disposal ponds (SDP), GV-1 (SDP) and GV-2 (SDP), at the Green Valley Wastewater Treatment Facility. Tables 2 through 5 and Appendix C contain the basic water quality data used for this section. When plotting results for duplicate samples, the highest concentration was used.

PDSI has water quality data for samples collected and analyzed from the late 1970s to the present. To portray current conditions, the most recent (through April 2006) sampling results were used. However, because some wells are not currently monitored, in some instances the data presented are several years old. For this reason, concentrations depicted on maps are accompanied by their sampling date so that the reader is aware that the information may be dated. Because water quality conditions can change over time, observations made using the older data are considered preliminary and require verification by additional sampling. Water quality data presented for well nests MH-13, MH-25, and MH-26, and well MH-30 are considered preliminary because the results are for the initial samples collected from these wells.

2.5.1 Sulfate Distribution

Groundwater containing elevated sulfate concentrations has been documented in the Green Valley area for many years. Early studies (PAG, 1983a and 1983b) identified elevated sulfate concentrations associated with the Sierrita, Twin Buttes, and Mission-Pima mines. Groundwater monitoring activities conducted since that time provide additional information concerning the spatial and temporal distribution of sulfate in the area.

The distribution of sulfate, based on the most recent samples from monitoring and production wells through April 2006 in the area east of the PDSTI, is shown in Figure 8. Table 2 lists the sulfate concentration data used for Figure 8. Numbers posted next to the well identification include the sulfate concentration (in mg/L) and the month and year of sample collection. Sulfate isoconcentration contours (isocons), inferred on the basis of the posted data, are shown and provide an interpretation of the limits of the sulfate plume based on existing data.

The majority of the data in Figure 8 is for samples collected from wells with large screened intervals. Concentration data for wells with short screened intervals, such as the well nests at MH-13, MH-25, and MH-26, are also shown. Data from short-screened interval wells are not necessarily comparable to data from wells with longer screen lengths because they have a dissimilar depth averaging of concentrations. Both data types are depicted in Figure 8 for completeness of areal coverage. The isocons in the vicinity of the nested wells were based on the highest measured concentration at the well nest.

2.5.1.1 Spatial Distribution of Sulfate

The spatial distribution of the sulfate plume is defined by groundwater samples collected from monitoring and production wells in the vicinity of the PDSTI and Green Valley. The spatial distribution can be divided into three components: lateral, longitudinal, and vertical. These relative directions are based on the general direction of groundwater movement in the area (Section 2.4.3). Longitudinal distribution is defined as being the north-northeasterly direction since it is the ultimate direction of groundwater movement from beneath the PDSTI. Lateral distribution is defined in the west-northwest to east-southeast direction representing the "sides" of the plume. Vertical distribution is based on data from co-located wells completed at different depths and depth-specific samples recovered from wells with long screen intervals.

2.5.1.2 Lateral Distribution

Data from 2005 and 2006 indicate that the east-southeast edge of the plume is west of wells GV-1, GV-2, and CW-3 and that the east-northeast edge of the plume is west of wells ESP-2 and ESP-3 and in the vicinity of ESP-1 and ESP-4. Data from 2004 for well CW-8 indicate the plume boundary was east of this location at that time.

The lateral extent of the plume to the west is defined by the IW- and MH-series wells in the interceptor wellfield. West of the interceptor wellfield the basin fill thins and the water table transitions into the bedrock complex. The extent of sulfate in basin fill west of MH-25 and MH-26 is not well defined due to the lack of monitoring wells north of the east edge of the PDSTI.

2.5.1.3 Longitudinal Distribution

The longitudinal distribution of sulfate to the south-southwest and north-northeast is shown in Figure 8. The eastern limit of the plume at its southern extent is defined by IW-2. Sulfate concentrations of samples collected from IW-2 dropped below 250 mg/L in late 2004 and have remained so since then.

The north-northeasterly extent of the plume is defined by wells CW-7 and the MH-26 well nest. CW-7 is the northern-most well with a sulfate concentration greater than 250 mg/L. The sulfate concentration in CW-7 was measured as 371 mg/L and 570 mg/L in samples reported by CWC and PDSI, respectively, for December 13, 2004 (Tables 2 and 3). Sulfate concentrations at the MH-26 well nest ranged from 20 mg/L to 1,570 mg/L in January 2006 (Figure D.5 in Appendix D). East of CW-7, the sulfate concentration in CW-9 was 60 mg/L in 2004. North of CW-7, the M- and ST-series wells had sulfate concentrations less than 100 mg/L when sampled in late 2003 (M wells) and early 2004 (ST wells). The only data available on sulfate northwest of CW-7 and the MH-26 well nest are for the I-series wells installed east of the Twin Buttes Mine pit for dewatering purposes (Terra Matrix, 1998). Sulfate concentrations ranged from 650 mg/L to 780 mg/L in samples collected from the I-series wells between 1999 and 2002. The lack of current information on water quality and water levels for the M- and I-series wells limits their use with respect to defining the northern extent of sulfate.

2.5.1.4 Vertical Distribution

The vertical distribution of sulfate in the basin fill is known from sampling at co-located well nests with screens completed at different elevations and depth-specific sampling from wells with long screened intervals. However, most monitoring and production wells do not provide depth-specific data because they were constructed with long screen intervals, typically penetrating the full extent of the basin fill aquifer. Because sampling from these wells is typically conducted from pump discharge that draws groundwater from the entire screened interval and mixes it in proportion to the proximity to the pump intake and hydraulic conductivity of the formation at any given depth, variations in concentration with depth are indistinguishable using this sampling protocol.

Well nests at MH-13, MH-25, and MH-26 were constructed as multiple wells at a single location or as wells containing separate screened intervals that can be isolated during sampling to allow collection of depth-specific information. Depth-specific samplers have also been used during spinner logging to evaluate changes in sulfate concentration with depth in some production wells.

Appendix D contains cross-sections through the plume showing sulfate concentrations to illustrate depth relationships for sulfate. At well nests MH-13, MH-25, and MH-26 sulfate concentrations greater than 250 mg/L persist to significant depths in the basin fill, although concentrations exhibit some variation with depth. At MH-13 the sulfate concentration decreases with depth, with sulfate concentrations of 1,750 mg/L, 970 mg/L, and 320 mg/L in samples collected from the upper (320-650 feet below land surface (bls)), middle (750-950 feet bls), and lower (1,050-1,350 feet bls) screened intervals in the basin fill, respectively (Figures D.3 and D.7 in Appendix D). At MH-25 and MH-26 sulfate concentrations in recent samples are less than 10 mg/L and 20 mg/L, respectively, at the top (above 538 feet bls) of the basin fill aquifer. Sulfate concentrations in basin fill at MH-25 increase to 1,640 mg/L and 1,410 mg/L at 580 to 680 feet bls in MH-25B and 731 to 901 feet bls in MH-25C, respectively. MH-25D, which is screened in Angelica Arkose from 951 to 1,081 feet bls, had a sulfate concentration of 600 mg/L, or approximately 43 percent of the concentration in overlying basin fill. In basin fill at MH-26, a sulfate concentration of 1,570 mg/L occurs at 620 to 730 feet bls in MH-26B (Figures D.3 and D.5 in Appendix D). MH-26C, which has 90 feet of screen in Angelica Arkose and 30 feet of screen in basin fill, had a sulfate concentration of 730 mg/L, or approximately 50 percent of the concentration in overlying basin fill

Three of the interceptor wells (IW-4, IW-9, and IW-12) were subjected to depth-specific sampling (ELMA, 2006). IW-12 is located in the northern half of the interceptor wellfield, whereas IW-4 and IW-9 are in the southern half. Sulfate concentrations in IW-12 declined from 1,060 mg/L at 510 feet bls to 900 mg/L at 557 feet bls. IW-4 sulfate concentrations increased from 1,460 mg/L at 517 feet bls to 1,560 mg/L at 888 feet bls. Sulfate concentrations in IW-9 ranged from 1,360 to 1,460 mg/L between 445 to 800 feet bls.

Depth-specific sampling was also conducted at ESP-4 (ELMA, 2004b). Samples from the static water level at approximately 336 feet bls to a depth of at least 550 feet bls were below 100 mg/L. At a depth of 785 feet bls the sulfate concentration was approximately 150 mg/L. Sulfate concentrations increased to 230 to 240 mg/L at depths of 880 and 975 feet bls, respectively. These findings suggest that the leading edge of the 250 mg/L concentrations on the east side of plume may be in deep, rather than near-surface groundwater zones.

The sulfate concentration of groundwater in bedrock downgradient of the PDSTI is not well defined. With the exception of MH-25D, no wells in the vicinity of the sulfate plume are screened exclusively in the bedrock and isolated from the basin fill aquifer. Production wells typically do not penetrate the bedrock because of its depth and low permeability. Those wells that are screened across or in very close proximity to the bedrock-basin fill contact may not provide reliable data on sulfate concentrations in the bedrock due to possible leakage from the overlying basin fill during pumping. Even if the bedrock contained elevated sulfate concentrations as suggested by sampling at MH-25D, the potential for significant mass loading from the bedrock to the basin fill can be expected to be low due to the low hydraulic conductivity of bedrock. The potential for exposure to sulfate in bedrock groundwater is probably low because water supply wells are typically not completed in bedrock as its low permeability makes it a poor water supply.

2.5.1.5 Temporal Distribution of Sulfate

Figure 9, from PAG (1983b), shows the distribution of sulfate at the PDSTI in 1982. Well identifiers on Figure 9 have been added to aid review. A comparison of the present distribution of sulfate (Figure 8) with the distribution in 1982 shows that the plume has advanced primarily north-northeastward. Lateral spreading to the east is also suggested by the increased concentrations in wells ESP-1 and ESP-4. The direction of plume migration is consistent with that indicated by water level contours shown on Figure 6.

The apparent rate of northerly plume migration can be estimated by the change in position of the 250 mg/L isocons from 1982 to 2006. The concentrations of sulfate at MH-1 and MH-12 straddle and define the location of the 250 mg/L isocon as being just north of MH-12 in May 1982 (Figure 9). Presently, the 250 mg/L isocon is north of CW-7 (Figure 8). The concentration of sulfate in CW-7 rose above 250 mg/L in January 1999 (Table 3). The travel time from May 1982 to January 1999 was approximately 6,090 days and the distance between the wells is approximately 9,900 feet, yielding an apparent velocity of approximately 590 feet per year. At that rate of northerly movement, the 250 mg/L isocon may have moved approximately 4,400 feet to the north since January 1999. This projection is only approximate, however, because the current migration rate may vary from the historical rate due to changes in aquifer conditions and groundwater pumping. Plume movement to the east is slower than to the north because the direction of groundwater flow is northerly.

The distribution of sulfate concentrations also changed over time. In 1982, concentrations greater than 1,000 mg/L were localized in the central portion of the plume (Figure 9). At present, concentrations exceeding 1,000 mg/L extend throughout most of the plume area, and concentrations exceeding 1,500 mg/L occur as far north as MH-26 (Figure 8).

Hydrographs of sulfate concentrations from the northern half (Figure 10) and southern half (Figure 11) of the interceptor wellfield show that sulfate concentrations in most wells increased steadily between 1980 and 2004 (Table C.3, Appendix C). However, sulfate concentrations, especially in the southern half, have been declining since early 2004, possibly in response to more aggressive pumping in the interceptor wellfield or changes in tailing seepage rates. In contrast to most of the IW wells, IW-1 and IW-2, located along the southern margin of the PDSTI, experienced consistent declines in sulfate concentrations from 1980 to 1990, flat to increasing sulfate concentrations from 1990 to 1998, and flat to declining sulfate concentrations from 1998 to present. The fastest declines in sulfate concentration at IW-1 and IW-2 have occurred since early 2004, again suggesting a response to more aggressive pumping at the interceptor wellfield.

2.5.2 Major Element Chemistry

The composition of groundwater can be characterized in terms of its major cations and anions and their relative concentrations, as well as other general water quality parameters such as total dissolved solids (TDS), hardness, and pH. Proximity to the PDSTI was used to evaluate major element concentration trends in water quality data. Wells within the sulfate plume were differentiated into groups regarded as proximal, medial, or distal to the PSDTI. Wells outside of the plume were identified as upgradient or downgradient from the sulfate plume (Figure 8). This division allows evaluation of changes in water chemistry as groundwater flows away from the tailing impoundment (proximal to distal) and commingles with the groundwater flowing northward beneath Green Valley. Selected wells were identified to characterize these regions. Wells selected for the groupings are:

- **Proximal Wells:** IW-1, IW-2, IW-3, IW-3a, IW-4, IW-5, IW-6a, IW-8, IW-9, IW-10, IW-11, IW-12, IW-13, IW-14, IW-15, IW-16, IW-17, IW-18, IW-19, IW-20, IW-21, IW-22, IW-23, and IW-24;
- **Medial Wells:** MH-11, MH-12, and MH-13;
- **Distal Wells:** ESP-1, ESP-4, CW-7, and CW-8;
- **Upgradient Wells:** GV-1, GV-2, S-1, and S-2; and
- **Downgradient Wells:** ESP-2 and ESP-3.

Table 4 summarizes the most recent analytical results for cations, anions, TDS, hardness, and pH compiled and tabulated with respect to their relationship to the impoundment. Data used to compile this table are presented as Table C.1 in Appendix C.

The summary data in Table 4 indicate that sulfate, chloride, calcium, magnesium, TDS, and hardness show a strong correlation with proximity to the tailing impoundment. In general, major element ion concentrations are greater in groundwater with elevated sulfate concentrations. The maximum and mean concentrations of major element ions decline moving from proximal to distal wells, although the concentration differences between the proximal and medial wells is sometimes slight. Chlorides, TDS, and hardness (a measure of the calcium and magnesium in water) are also correlated with sulfate and their levels are elevated in the sulfate plume.

The pH of the well samples does not show a strong correlation to sulfate. The average pH in the proximal wells is 7.24 and decreases to 7.12 in the medial wells and 7.13 in the distal wells. This indicates that the sulfate-bearing groundwater has neutral pH. The pHs of upgradient and downgradient wells are 7.46 and 7.75, respectively, perhaps reflecting the influence of recharge along the Santa Cruz River.

Concentration data for recent samples from selected wells (Table C.1 in Appendix C) were converted to "milliequivalents" and used to construct trilinear diagrams that plot the combination of cations and anions in a single field (Figure 12). The plotted points demonstrate that waters from the various wells follow a distinctive trend. Proximal and medial wells within the plume contain calcium-sulfate water, whereas the upgradient and downgradient wells outside of the impacted area contain calcium-bicarbonate water. In general, distal wells have cation-anion combinations that fall between the combinations at proximal and medial wells, and unimpacted wells. An exception to the proximal wells is IW-2, a proximal well, which plots in the vicinity of upgradient and downgradient wells due to the effects of dilution by upgradient water from pumping in the interceptor wellfield, as noted in Section 2.5.1.5.

As shown by Figure 12, most well water chemistries fall along a line between wells within and outside of the plume. This suggests that a continuum of mixing exists between the two end-member waters. This is logical considering that (1) the sulfate-impacted water mixes with unimpacted groundwater from upgradient areas, (2) the process water seeping from the tailing impoundment is derived from unimpacted groundwater from the upgradient Canoa wellfield along the Santa Cruz River south of Green Valley, and (3) impacted water from the interceptor wellfield is re-used in the mill.

2.5.3 Metals

Metals analyses for samples from wells in the interceptor wellfield (proximal wells) (Table C.2, Appendix C) were compiled and evaluated to characterize metals from the PDSTI. The data were compared with Arizona numeric Aquifer Water Quality Standards (AWQS)

(A.A.C. R18-11-405) to characterize the relative magnitude of metals concentrations. The metals with AWQS include:

Metal	AWQS (mg/L)
Antimony	0.006
Arsenic	0.05
Barium	2
Beryllium	0.004
Cadmium	0.005
Chromium	0.1
Lead	0.05
Mercury	0.002
Nickel	0.1
Selenium	0.05
Thallium	0.002

The U.S. Environmental Protection Agency has established a maximum contaminant level (MCL) for arsenic in public drinking water supplies at 0.010 mg/L effective January 2006 and enforceable in 2007. Therefore, arsenic results will be compared with this standard although the applicable AWQS has not been established at this level.

Table 5 summarizes metals data for the interceptor wells (IW-series) for the past ten years (1997 to April 2006). The metals data were reported as dissolved metals because the samples were filtered in the field prior to preserving the sample for transport to the laboratory. Based on the data in Table 5, metals concentrations in groundwater samples from the interceptor wellfield rarely exceed AWQSs. This indicates that the tailing impoundment is not a source of metals to the groundwater.

Chromium, lead, nickel, and thallium were detected in concentrations exceeding their respective AWQS in 1 percent or fewer of sample analyses. The AWQS for lead (0.05 mg/L) was exceeded in one sample from IW-12 in 1997, but all subsequent samples were below the standard. Nickel and chromium were detected in three samples, and thallium was detected in one sample at concentrations exceeding their respective AWQSs in December 2004, but these results are inconsistent with results from samples collected before and after this sample. Because of the large number of samples (more than 230 samples), low exceedance frequency, and the lack of exceedences in subsequent samples, the few elevated detections of chromium, lead, nickel and thallium are not considered significant and could be the result of laboratory error.

2.6 Preliminary Conceptual Model for the Groundwater Sulfate Plume

The conceptual model describes known and potential sources of sulfate and the movement of sulfate in groundwater at the PDSTI. The conceptual model provides a framework for summarizing what is known about the origin and migration of the sulfate plume and identifying what additional information may be needed to fully characterize it.

2.6.1 Sulfate Sources

Based on groundwater monitoring, a known source of sulfate is seepage from the PDSTI to the underling basin fill aquifer. The seepage results from the gravity drainage of the pore water through the PDSTI. The pore water consists of original slurry water and water that infiltrates into the tailing from the reclaim pond on top of the impoundment.

Sulfate in the tailing water results from the dissolution of sulfate salts and the oxidation of sulfide minerals during the milling and flotation process that produces the tailing, and the use of sulfate-bearing water from the interceptor wellfield in the mill circuit. The tailing slurry water, reclaim pond water, and interceptor wellfield water are chemically similar with respect to sulfate and other major element ion concentrations (ELMA, 1989).

The tailing impoundment represents a finite source of sulfate that will eventually cease following the end of mining and mineral processing, when tailing is no longer deposited and residual moisture drains from the tailing material. The rate of residual seepage will further diminish as the surface of the impoundment is capped and revegetated to minimize infiltration from precipitation.

Groundwater in the bedrock upgradient of the tailing impoundment is a second source of sulfate to the basin fill beneath the impoundment. Groundwater sulfate concentrations in bedrock upgradient of the tailing impoundment are generally in the range of 100 to 3,000 mg/L (ELMA, 2001). However, the contribution of sulfate by bedrock recharge is likely minor compared to the tailing because the low permeability of bedrock (Section 2.4.2) would limit the sulfate mass flux from the upgradient area.

Other potential sources of sulfate may occur outside the PDSTI. As discussed above, PAG studies identified tailing impoundments at other mines as potential sources. Based on historical sampling, groundwater in the vicinity of the Twin Buttes Mine, at the north end of the sulfate plume, may contain sulfate (Section 2.5.1). Another potential source of sulfate is groundwater in the vicinity of the Santa Cruz River. As documented by Laney (1972) and PAG (1983a), groundwater in the vicinity of the Santa Cruz River in this part of the Tucson basin can contain greater than 250 mg/L sulfate (Plate 5 in PAG 1983a). The sulfate is attributed to groundwater derived from gypsiferous sediment east of the Santa Cruz fault, but irrigation return flow may also add TDS.

2.6.2 Movement of Sulfate in Groundwater

Sulfate-containing seepage from the tailing impoundment infiltrates into the basin fill, mixes with groundwater recharge from the upgradient bedrock and flows eastward. Sulfate-impacted groundwater is intercepted through groundwater pumping within the interceptor wellfield. Impacted groundwater that is not intercepted at the wellfield or that has already flowed downgradient of the interceptor wellfield flows north-northeasterly as it enters the northerly flowing regional groundwater system in the basin fill aquifer.

Sulfate is transported at the same rate as the groundwater flow because it is a conservative ion. The direction and velocity of groundwater flow and sulfate transport are determined by the hydraulic properties of the basin fill aquifer and the hydraulic gradients prevailing along the flow path. In addition to regional conditions, groundwater flow and sulfate transport are influenced by local sites of groundwater pumping and recharge. For example, pumping at a well in the vicinity of the plume can induce hydraulic gradients that cause the plume to migrate toward the well. Groundwater pumping in the Green Valley area has increased over time to meet increasing demand for drinking water, as illustrated by the 70% increase in annual groundwater pumping by CWC from 1986 (546.3 million gallons) to 2005 (929.8 million gallons). The collective influence of pumping at drinking water supply wells located near the plume can influence sulfate migration and the location of the plume.

Within the plume, elevated sulfate occurs throughout the thickness of the saturated basin fill aquifer with the exception of the uppermost portions of the aquifer at MH-25, MH-26, and ESP-4 (Section 2.5.1.4). Although existing information indicates some variations in the hydraulic conductivity of the basin fill aquifer with depth (e.g., low permeability Pantano Formation at depth in MH-13 and higher flows at depth in ESP-4), large-scale features that would cause preferential flow paths, such as laterally extensive aquitards or high permeability units within the basin fill, have not been identified. The ACP (Section 3) will further evaluate the vertical variation of hydraulic properties in the basin fill. Based on the results of hydraulic testing of bedrock at MH-25 within the plume and elsewhere in the vicinity of the PDSTI (Section 2.4.2), the bedrock is significantly less permeable than the overlying basin fill aquifer. For this reason, the bedrock aquifer is not considered to have significant groundwater flow or potential to transport sulfate relative to the basin fill aquifer.

3. AQUIFER CHARACTERIZATION PLAN

3.1 Aquifer Characterization Plan (ACP) Objectives and Data Needs

3.1.1 ACP Objectives

The objectives of the ACP are to address the MO requirements to characterize the sulfate plume and to collect data sufficient to complete the FS. Based on Sections III.A and III.C of the MO, the ACP will:

- complete a well inventory to identify drinking water wells within one mile downgradient and cross-gradient of the outer edge of the sulfate plume,
- determine the vertical and horizontal extent of the sulfate plume,
- evaluate the fate and transport of the outer edge of the sulfate plume, and
- evaluate the effectiveness of the interceptor wellfield as a groundwater sulfate control system.

3.1.2 Data Needs

Addressing the MO requires the following data:

- locations of drinking water wells within one mile downgradient and cross-gradient of the plume,
- sulfate concentration data collected at different locations and depths,
- water level measurements to document potentiometric conditions,
- information on the structure and hydraulic properties of the aquifer, and
- information on the operation of the interceptor wellfield, sulfate concentrations in the wellfield, and water levels in the vicinity of the wellfield.

A numerical model for groundwater flow and solute transport will be developed to evaluate the fate and transport of sulfate. In addition to the data identified above, information quantifying existing and future sources and sinks of groundwater will be needed to construct the model.

Data needs for the FS include: water quality data pertinent to assessing potential treatment technologies, the current and future pumping rates for existing wells, expected future pumping rates for planned wells, and design specifications for existing and future water distribution and storage systems. Water quality data for assessing treatability will be developed under the ACP, whereas the FS (Section 5) will consider information on water treatment, current and future water supply and storage infrastructure, and the costs and benefits of mitigation alternatives.

The ACP consists of the following five tasks that will collect the data needed to address the MO requirements.

- Task 1 – Well Inventory
- Task 2 – Plume Characterization
- Task 3 – Evaluation of PDSI's Sulfate Control System
- Task 4 – Sulfate Fate and Transport Evaluation
- Task 5 – Preparation of the Aquifer Characterization Report

Data needs and the ACP tasks that address them are briefly described below and summarized in Table 6. Sections 3.2 through 3.6 describe the individual ACP tasks.

- **Well Inventory** – The locations of drinking water supply wells will be identified by the well inventory for Task 1 (Section 3.2).

- **Horizontal Extent of Sulfate Plume** – As shown in Figures 3 and 8, the general horizontal extent of the plume is known to within approximately 3,000 to 5,000 feet based on available data. The eastern extent of the plume is bounded by wells GV-1, GV-2, ESP-1, ESP-2, ESP-3, and ESP-4 with concentrations less than 250 mg/L. Additional data is needed along the southeast boundary of the plume where there are no wells or no recent data, such as at CW-3. Few wells are available to define the northern boundary of the plume. Sulfate exceeds 250 mg/L at the MH-26 well nest and CW-7, but was less than 250 mg/L in samples collected from CW-9 in 2004 and the M-series wells in 2003. Recent data are not available for sulfate concentrations in the I-series wells east of the Twin Buttes pit. Task 2 contains groundwater monitoring (Section 3.3.2) and the installation and sampling of additional wells (Section 3.3.4) to further delineate the horizontal extent of the plume.

- **Vertical Distributions of Sulfate** – Ongoing monitoring of nested monitoring wells (MH-13, MH-25, and MH-26) by PDSI will provide information on the vertical distribution of sulfate. Additional monitoring wells will be installed for Task 2 (Section 3.3.4) either as co-located well nests or with multiple screens to characterize the three-dimensional aspects of the plume. Depth-specific water quality sampling in existing wells at the east and north ends of the plume will be conducted for Task 2 (Section 3.3.3) to investigate the vertical distribution of sulfate with depth. Depth-specific sampling will also be conducted at selected monitoring wells where well access is available.

- **Water Level and Water Quality Information** – Water level and water quality data will be updated in areas lacking current information and the spatial coverage of water level and water quality data will be expanded. Routine groundwater monitoring by PDSI will be used to characterize water levels and water quality within the plume. Additional groundwater monitoring will be conducted for Task 2 (Section 3.3.2) to provide water level and water quality information in areas not monitored by PDSI or in areas for which available data are several years old (e.g., wells at the Twin Buttes Mine and some drinking water supply wells). Groundwater monitoring will collect contemporaneous water level and water quality data for a large geographic area outside of the plume. These data are needed to provide information on the regional groundwater flow system for calibration of the groundwater flow model for Task 4 (Section 3.5) and for characterizing background water quality conditions.

- **Aquifer Structure and Hydraulic Properties** – Existing data on the aquifer structure and hydraulic properties will be compiled for Task 2. Depth-specific flow testing in wells at the east and north ends of the plume will be conducted for Task 2 (Section 3.3.3) to identify any apparent variations in permeability with depth. Aquifer testing to be conducted at monitoring wells installed for Task 2 (Section 3.3.4) will characterize the horizontal and vertical distribution of hydraulic properties.

- **Groundwater Control System Data** – Information regarding water levels in the vicinity of the interceptor wellfield, interceptor wellfield pumping, and sulfate concentrations in extracted groundwater will be compiled and analyzed in Task 3 (Section 3.4) to evaluate flow to the wellfield and wellfield mass capture.

- **Quantification of Groundwater Sources and Sinks** – Groundwater sources (recharge) and sinks (pumping) will be documented for use in the groundwater flow model for Task 4 (Section 3.5). Recharge to the aquifer from the PDSTI, ephemeral flows in the Santa Cruz River, and other sources, such as semi-permanent ponds or the Pima County wastewater treatment facility, will be documented or estimated for the groundwater flow model. Current and future expected groundwater pumping from water supply, irrigation, and industrial wells will be obtained from well owners or estimated using available information.

3.2 Task 1 - Well Inventory

A well inventory will be conducted to identify all wells within one mile of the sulfate plume. Wells within one mile downgradient and cross-gradient of the outer edge of the plume will be categorized on the basis of water use to identify wells that may supply drinking water.

The well inventory will be based on the Arizona Department of Water Resources (ADWR) Well Registry Database which contains records for all registered wells in Arizona. Records in the well registry pertain to a variety of types of installations including water supply wells (private, domestic, and municipal), environmental monitoring wells, remediation pumping wells, piezometers, geotechnical borings, mineral exploration borings, and abandoned wells. Information potentially available for individual wells includes the well registry identification number, cadastral and Universal Transverse Mercator (UTM) coordinates, well use, water use, installation data, well construction information, pumping information, and well owner.

The ADWR Well Registry Database is provided in a Geographic Information System (GIS) format which allows the use of spatial queries to identify and extract well information based on the location of the well. A spatial query will be constructed using a geo-referenced shape file defining the outer edge of the sulfate plume defined by the 250 mg/L contour (Figure 8). The shape file will be used to query the database and identify all wells within one mile of the plume's downgradient and cross-gradient edge.

Well locations in the ADWR database are described by cadastral coordinates based on township, range, and section. Most well locations are described to the "quarter, quarter, quarter section"; an area of 10 acres or 660 feet by 660 feet. The database assigns UTM coordinates for the well to the midpoint of the area, although the well can be anywhere in the 10-acre area. To ensure the well inventory is comprehensive and identifies all wells potentially within one mile downgradient and cross-gradient of the plume, a safety factor will be added to the one-mile search radius to account for the uncertainty in well location due to cadastral coordinates. Because of the safety factor, wells that are farther than one mile from the plume may be identified. Wells will be removed from the set of wells identified using the safety factor only if they can be verified as being farther than one mile from the plume based on survey information or more detailed cadastral coordinates.

The well inventory records will be sorted by well use and water use to identify wells used to supply drinking water. To augment the well inventory, public and semipublic water systems on file with ADEQ will be checked against the well inventory to identify water systems. Also, the ADWR Water Providers database will be used to identify the service areas of municipal water providers in the area.

The well inventory is an important step in identifying potentially impacted wells. The well inventory will begin shortly after the ACP is finalized and will be conducted initially using the 250 mg/L sulfate contour shown in Figures 8. The well inventory may be revised if the plume defined by the results of characterization work for Task 2 indicate a significantly different shape for the plume.

3.3 Task 2 - Plume Characterization

Plume characterization for Task 2 consists of data compilation and evaluation activities as well as field investigations. The data compilation and evaluation activities will ensure that the existing data used to characterize the plume are complete and verified. The field investigations focus on characterizing water level and water quality conditions in the regional aquifer, determining the vertical and lateral distribution of sulfate in the plume, and estimating aquifer hydraulic properties. The QAPP in Appendix E presents the data quality objectives (DQOs) for plume characterization. In summary, the DQOs are to:

- Define the extent of groundwater with sulfate in excess of 250 mg/L based on depth-specific groundwater samples collected from existing production wells and groundwater samples from new and existing monitoring wells.
- Characterize the structure and permeability of the basin fill aquifer through geologic analysis of cuttings from drill holes, aquifer testing, and flow logging of production wells.
- Characterize the groundwater flow system through water level measurements.
- Collect water quality data needed to evaluate water treatment.

The plume characterization includes the following subtasks:

- data compilation and evaluation,
- groundwater monitoring to augment the existing water level and water quality data,
- depth-specific groundwater sampling at existing wells to determine the vertical extent of sulfate and flow logging at existing production wells to evaluate relative well inflows as a function of depth, and
- installation and testing of monitoring wells to define the eastern and northern extents of sulfate.

3.3.1 Task 2.1 - Data Compilation and Evaluation

The data compilation and evaluation will focus on assembling and assessing information on (1) the hydraulic properties of the geologic materials, (2) the subsurface distribution of bedrock, and (3) the water quality of area wells. A secondary objective will be to assemble and evaluate all available geologic logs for wells in the area.

The hydraulic properties of geologic materials are critical information for developing the conceptual and numerical models. The hydraulic conductivity data reported in Table 1 are taken from a variety of reports. As a quality assurance check, the test methods, data, and analysis methods for the tests will be evaluated to assess test reliability. Additional sources of hydraulic data will also be researched.

The depth to bedrock provides important information on the effective thickness of the basin fill aquifer which is needed for construction of the groundwater flow model and estimation of groundwater flow. ELMA & DM (1994) reported bedrock depth in the area of interest using compilations of geologic data. These data will be evaluated and compared to bedrock elevations from borings. Information for any exploration borings in the area will be obtained from the PDSI mine department to further check the bedrock elevation data. Additionally, geophysical data for the area will be reviewed for information on bedrock depth.

Limited water quality data are available for water supply and irrigation wells in the area, and although water quality sampling of these wells is proposed for Task 2.2 (Section 3.3.2), historical water quality data are lacking. The owners of water supply and irrigation wells will be contacted to obtain any water quality information they are willing to share. This data will then be compiled and evaluated to document existing conditions and to identify any water quality changes over time. Well owners will also be asked for access to geologic logs for wells if that information is not available elsewhere.

3.3.2 Task 2.2 - Groundwater Monitoring

PDSI routinely monitors groundwater in its monitoring and production wells. The PDSI monitoring data are used to characterize the PDSTI area and the sulfate plume. The data collected by PDSI's ongoing monitoring will be used for this project. Additionally, a water level and groundwater sampling program is proposed to augment the PDSI monitoring by collecting information on local and regional water levels outside the PDSTI and sulfate plume areas. This information is fundamental to gain a better understanding of regional groundwater flow and its affect on plume migration.

To obtain information for the area outside of the PDSTI and the plume, the monitoring program will attempt to access and sample or obtain current data on wells owned by other parties. The Twin Buttes Mine, CWC, Green Valley Domestic Water Improvement District, Farmers Investment Company, and private individuals are examples of entities that will be approached for well access or sampling data. Thus, the success of this task will depend on cooperation from well owners and local water companies.

The groundwater monitoring task includes collecting static water level measurements and obtaining a groundwater sample for analysis of sulfate and other constituents unless equivalent information is available from the well owner. The collected information will be used to describe current water table conditions and background water quality; both of which are needed for modeling the sulfate plume. Therefore, an objective of this task is to obtain large geographic coverage in the area around the PDSTI.

The groundwater monitoring program will collect data twice; once in winter and once in summer to characterize the annual extremes in water elevation. Access agreements will be obtained from cooperating property owners in order to measure water levels and to collect groundwater samples. The ability to measure water levels will be limited by whether the well has an access port or sounding tube.

Groundwater samples will be collected and submitted to an Arizona-certified laboratory for analysis. The samples will be analyzed for calcium, magnesium, sodium, potassium, chloride, sulfate, alkalinity, fluoride, nitrate, nitrite, and pH to characterize sulfate and the general water chemistry. Water samples from select wells may also be analyzed for the following constituents needed to assess water treatment for the FS: aluminum, ammonia, barium, chemical oxygen demand, ferrous and total iron, manganese, phosphate, selenium, soluble and colloidal silica, strontium, sulfide, total organic carbon, silt density index, turbidity, and bacteria. Sampling and analysis will be conducted according to the methods described in the QAPP (Appendix E). Specific conductance, pH, and temperature will be measured in the field during groundwater sample collection. Groundwater samples will be collected as close to the wellhead as is feasible, upstream of any filtration, sand cyclones, chlorine or other chemical additions to the well water. The results of analyses will be included in task reports and will also be provided to the well owner.

3.3.3 Task 2.3 - Depth-Specific Groundwater Sampling at Existing Wells

Many of the wells in, or proximal to, the sulfate plume have screened intervals of 600 feet or more. It is only since 2005 that nested monitoring wells have been installed to collect depth-specific information (e.g., MH-13 A, B, C; MH-25 A, B, C/D; and MH-26 A, B, C). Depth-specific sampling and spinner logging has been used to determine the vertical variation of sulfate and inflow at several interceptor wellfield wells and at ESP-4 (ELMA, 2004b and 2006). The information collected by depth-specific sampling and inflow logging is useful for identifying water quality variations with depth, evaluating changes in relative permeability with depth, and assessing whether a well can be modified to minimize production from a sulfate-bearing horizon.

3.3.3.1 Depth-Specific Sampling of Pumping Wells

Depth specific groundwater sampling for sulfate will be conducted at pumping wells ESP-1, ESP-2, ESP-3, and ESP-4 to evaluate the northeastern extent of sulfate, at CW-7 to evaluate the northern extent of sulfate, and at CW-8 to test the eastern extent of sulfate. Testing at CWC wells is contingent on their permission for access and testing. Because ESP-1, ESP-2, ESP-3, and ESP-4 are pumping wells equipped with pumps and riser pipes, sampling will be conducted using a procedure that does not require removal of the pump string. The sampling procedure, developed and licensed by BESST Inc. (BESST), uses small diameter equipment that can be inserted into wells through a small (less than 1-inch) hole drilled in the surface casing. In conjunction with depth-specific sampling, dynamic inflow profiling will be conducted using BESST's dye tracer injection system, which releases a small amount of dye at a specific depth and monitors its recovery in the discharge stream. The dynamic inflow profiling will be used to characterize the relative permeability with depth in the screened interval of the wells tested.

The status of pumps and piping in CW-7 and CW-8 is uncertain. If the wells are equipped with pumps, the BESST testing method can be used. If the wells are not equipped with pumps, the BESST methods will be employed by installing a temporary pump in the well.

Because the BESST sampling technique has not been used before at the site, the method will be tested at ESP-4 and the results compared to the results of previous spinner logging to evaluate the comparability of results. Groundwater sampling protocols are described in the

QAPP (Appendix E). Groundwater samples collected by depth-specific methods will be analyzed for sulfate only (Appendix E).

3.3.3.2 Depth-Specific Sampling of Monitoring Wells

Depth-specific groundwater samples will be collected at monitoring wells MH-11 and MH-12 to determine any sulfate zoning with depth in the medial part of the plume. Wells MH-11 and MH-12 are monitored by PDSI. Depending on the configuration of the wellhead, depth-specific samples will be collected by using either the BESST system described above, a discrete interval sampler, or a low flow submersible pump lowered to various depths in the screened interval.

3.3.4 Task 2.4 - Offsite Well Installation and Testing

Additional monitoring wells are proposed at six locations off the PDSI property to further define the extent of the sulfate plume, to provide installations for ongoing monitoring, to characterize aquifer materials and hydraulic properties, and to determine bedrock depth. Well installation will be focused in the northern and eastern portions of the plume because these areas have the greatest uncertainty in the distribution of sulfate and are of concern with respect to future plume migration. The scope of this task will be dependent on information gained as the task progresses. If during this task, newly installed offsite wells are determined to be within the plume, a determination will be made as to whether additional wells need to be installed to meet the data quality objective of defining the extent of the plume.

Figure 13 shows the approximate locations of proposed monitoring wells. Table 7 lists the proposed wells, their design objectives, and land ownership. Land access for drilling and well installation is a major issue because the Green Valley area is extensively developed. Offsite well locations are proposed on a combination of private and public lands. Access agreements will have to be negotiated with private land owners prior to drilling. Potential well locations on public property are either along the Pima County roadway right of way or in areas administered by the Arizona State Land Department (ASLD). Land use applications will be submitted for work on public land. Based on prior experience at MH-13, MH-25, and MH-26, obtaining access to ASLD land can take about 12 months. The exact locations of the proposed wells are provisional subject to successful negotiation of site access.

Well locations and design objectives are based on position in the plume, the level of information available in the area of the proposed well, and the potential long-term use of the monitoring well. Some well sites on the east side of the plume are expected to be between the plume and existing drinking water supply wells, allowing them to be useful as sentinel wells and for plume definition. Well designs in Table 7 are subject to modification based on the results of other plume characterization tasks that will provide information on the subsurface distribution of sulfate (e.g., depth-specific groundwater sampling and groundwater monitoring) and site-specific conditions observed during drilling (e.g., subsurface lithology and water quality).

Co-located nested well installations are recommended at the leading edge of the plume to collect information on vertical zoning and to monitor future plume movement. The primary objective of wells on the east side of plume is to determine the lateral extent of the plume. For this reason, some wells on the east side of the plume incorporate multiple screens in a single well to allow initial and periodic, depth-specific sampling, and routine sampling over the entire screened interval. Sampling these wells from the entire screened interval should be sufficient to monitor for changes in sulfate concentration transverse to the direction of plume movement. Some wells will be installed at the location of an existing well to provide additional vertical characterization.

Monitoring wells will be installed using air and mud rotary methods. Reverse circulation air rotary drilling will be used to install a pilot hole to the bottom of the basin fill and to collect cuttings and water samples with depth. Reconnaissance water samples will be collected from the air rotary return and analyzed in the field using an electrical conductivity meter and a portable spectrophotometer to characterize TDS and sulfate concentrations with depth during drilling. Water samples for laboratory analysis of sulfate may be collected to confirm field measurements if sufficient sample is available. Well designs will be guided by the results of lithologic logging and water quality analyses. Mud rotary drilling will be used to ream out the pilot hole and install any additional wells at the site.

Drilling, well installation, and development methods are described in the QAPP (Appendix E). Each new well will be developed to remove sediment and drilling fluids. After development, short duration (12 to 24 hour) pumping tests will be conducted at each well. At the conclusion of the pumping test, a water quality sample will be collected from each well for analysis of sulfate and other major element ions for characterizing general water chemistry. All new wells will be surveyed by PDSI following completion of their surface casings. Water level measurements and water quality samples will be collected from the new wells on a quarterly basis until a long-term monitoring plan is developed pursuant to the Mitigation Plan (Section 5). Water level measurement, water quality sampling, and pumping test methods are described in the QAPP (Appendix E).

3.4 Task 3 - Evaluation of PDSI Groundwater Sulfate Control System

Task 3 analyzes the effectiveness of PDSI's existing sulfate source control system in accordance with the requirement in Section III.C.4 of the MO. Water level, water quality, and wellfield pumping data will be used to evaluate flow to the wellfield and wellfield mass capture.

3.4.1 Review of Source Control Pumping at Interceptor Wellfield

The history of sulfate migration control by the interceptor wellfield will be reviewed including the geology of the wellfield area, the duration of operation, and annual groundwater pumping. The current infrastructure of the system will be described with respect to basic flow routing, design capacities, and water use.

3.4.2 Evaluation of Interceptor Wellfield Effectiveness

The effectiveness of the existing groundwater pumping system will be evaluated based on its operational availability, its mass capture, and hydraulic gradients created by pumping. Operational, water level, pumping rate, and water quality data will be compiled and used to evaluate the effectiveness of the current system. Parameters such as well and wellfield availability, and total and well-by-well pumping will be used to determine operational effectiveness. Water level, pumping, and water quality data will be used to evaluate mass capture.

3.4.2.1 Water Level Data

Water levels in the vicinity of the interceptor wellfield will be used to evaluate the saturated thickness of the aquifer. As discussed in Appendix A, the depth to bedrock is greater in the southern half of the wellfield than the northern half. For this reason, the saturated thickness of the aquifer pumped by the interceptor wells is greater in the south half of the wellfield than in the north half. Other factors held constant, the yield of a pumping well is approximately proportional to its saturated thickness. As water levels in the wellfield area decline due to drawdown caused by pumping and regional water table decline, well yields will also decline. The relationships between water level, saturated thickness, and well yield will be evaluated to assess potential operational constraints on the interceptor wellfield. Additionally, water level data for monitoring wells in the wellfield will be used to examine hydraulic gradients and the local potentiometric surface in the vicinity of the wellfield.

3.4.2.2 Groundwater Pumping

Pumping data will be compiled to document the productivity of individual wells and the wellfield as a whole. The data will be reviewed to identify any significant differences in well yields across the wellfield.

3.4.2.3 Wellfield Mass Capture

Mass capture of individual wells will be estimated as the product of their average pumping rate and average sulfate concentration. The results will be summed to estimate the total wellfield mass capture. Examination of sulfate concentrations in the interceptor wells (Figure 8) indicates that sulfate concentrations do not vary significantly from north to south. Therefore, mass capture across the wellfield is primarily a function of well yield and duration of operation.

3.4.2.4 Estimation of Flow to Wellfield

Groundwater flow to the wellfield will be used to estimate its effectiveness in capturing flow in the basin fill beneath the tailing impoundment. The groundwater flow to the wellfield will be estimated using hydraulic gradient, saturated thickness, and hydraulic conductivity data for the wellfield area. The difference between the calculated flow to the wellfield and the total wellfield pumpage will provide a preliminary estimate of wellfield capture.

3.4.3 Modeling of Wellfield Hydraulics

Analytical or finite difference numerical models may be used to evaluate the hydraulic capture and interference between pumping wells. The objective of the modeling would be to optimize wellfield capture and evaluate the benefits and disadvantages of additional extraction wells. Recommendations for optimizing source control pumping will be developed using the evaluation of wellfield effectiveness and numerical modeling of hydraulic capture.

3.5 Task 4 - Sulfate Fate and Transport Evaluation

The information collected to meet the data needs described in Section 3.1.2 will be used to refine the preliminary conceptual model in Section 2.6. Numerical groundwater flow and transport models will then be developed based on the refined conceptual model to further evaluate the fate and transport of sulfate originating from the PDSTI and, as described below, other sources identified during execution of this work plan. The modeling will include development and use of a regional-scale saturated flow and transport model that will encompass an area that extends in the east-west direction from at least the western edge of the tailing impoundment eastward to the central portion of the basin, and in the north-south direction from several miles upgradient (south) of the tailing impoundment to approximately one mile downgradient (north) of the Twin Buttes Mine. The actual area of the model may be adjusted as deemed necessary based on information gathered as part of the ACP.

The modeling effort will make use of and build upon existing numerical models developed and used for the site (e.g., ELMA & DM, 1994). Boundary conditions and other features of the existing models may be incorporated in whole or in part into the new regional model subject to verification of their adequacy. Existing model inputs such as pumping rate files pertaining to operation of industrial wells and other production wells within the model domain will be updated and incorporated as needed.

The goals of the modeling will be to:

- Calibrate the regional model to reproduce with acceptable accuracy past measured hydraulic head and sulfate distributions within the model domain.
- Examine the groundwater flow dynamics under existing conditions to understand how groundwater pumping at different locations in the basin influences the current distribution of sulfate.
- Predict future hydraulic head and sulfate distributions under various possible mitigation scenarios, such as existing interceptor wellfield pumping only or additional groundwater pumping by the interceptor wellfield, or under long-term conditions such as increased water supply pumping.

3.5.1 Compile Information on Groundwater Pumping and Recharge

Available pumping information for production wells within the model domain will be compiled and analyzed for input to the regional flow and transport model. It is anticipated that this effort will entail updating existing files of pumping rate information used in previous site models. Any recently installed production wells will be included, as will any existing wells that may be brought into a potentially expanded model domain. Water supply plans for local water companies will be used to estimate future groundwater pumping.

Areal recharge estimates resulting from infiltration by precipitation or as a result of streamflow will be developed for input to the model. This process will also build, to the extent appropriate, on recharge data incorporated into existing site numerical models.

The rate of seepage and sulfate concentration of the seepage over time at the PDSTI will be evaluated and used in the regional groundwater flow and transport model. Seepage will be estimated from a variety of sources including site-specific information on the tailing impoundment water balance and groundwater conditions beneath the impoundment.

Sources of elevated sulfate concentrations within the regional aquifer that are unrelated to PDSTI, such as naturally occurring sources or other mining properties, will be evaluated and incorporated as appropriate into the regional flow and transport model. Naturally occurring sulfate sources, and other background sources, may have resulted in past detections of elevated sulfate in some wells located near the Santa Cruz River (PAG, 1983a). Groundwater quality samples collected in 1981 and 1982 showed elevated sulfate in wells immediately downgradient of the PDSTI, low sulfate concentrations (<100 mg/L) between these wells and wells adjacent to the Santa Cruz River, and concentrations exceeding 100 mg/L in many of the wells along the Santa Cruz River. Groundwater derived from gypsiferous sediment is the suspected origin of the elevated concentrations along the Santa Cruz River, although agricultural sources may also have contributed.

3.5.2 Sulfate Transport Under Current and Future Conditions

The regional-scale numerical model developed to evaluate the fate and transport of sulfate in the regional aquifer will be calibrated to past and present measured hydraulic heads and sulfate concentrations. The calibrated model will be used to predict future conditions of hydraulic head and sulfate distribution in the regional aquifer. Simulations of future conditions will include the effects of pumping from future wells and water supply development described by water system plans.

The regional model will incorporate elements of existing site models such as boundary conditions, past pumping rate information, and recharge by precipitation and streamflow, as appropriate. It will also expand upon previous modeling efforts by including multiple aquifer layers to enable three-dimensional simulations, and will use different hydrogeological properties, sources and sinks, and boundary conditions based on most current information.

At a minimum, it is anticipated that the model will be used to simulate future conditions assuming:

- Continued operation of existing sulfate control measures (i.e., the interceptor wellfield).
- Augmentation of existing sulfate control measures with additional sulfate control strategies.

The results of these simulations will be used to evaluate the potential future migration of sulfate and the effectiveness of different groundwater pumping schemes and/or the use of institutional controls and natural attenuation as potential mitigation actions. The groundwater flow and transport simulations will be used to provide conceptual design bases for potential mitigation actions.

3.6 Task 5 - Aquifer Characterization Report

Section III.C of the MO requires PDSI to submit an Aquifer Characterization Report to ADEQ. Pursuant to the MO, the Aquifer Characterization Report will address:

- Current sulfate plume delineation.
- Sulfate fate and transport.
- Identification of all registered private drinking water wells and public drinking water system wells.
- Analysis of the effectiveness of PDSI's current groundwater sulfate control system.

The Aquifer Characterization Report will consist of reports prepared at the conclusion of each task. This reporting process is recommended so that information on individual tasks can be made available to ADEQ expeditiously rather than waiting to assemble all the information into a single final report.

Figure 14 shows a schedule for the ACP tasks. Work for some the ACP tasks is expected to take more than a year to complete. The submittal of periodic task reports will provide the results of the investigation to ADEQ in a sequenced fashion allowing time for ADEQ to evaluate the results and provide comments as the investigation progresses. The schedule is discussed further in Section 6.

The following task reports will be submitted to ADEQ as the Aquifer Characterization Report (Figure 14).

- Well Inventory Report (Task 1)
- Data Compilation and Evaluation Report (Task 2.1)
- Groundwater Monitoring Data Report for First Sampling Event (Task 2.2)
- Results of Depth-Specific Sampling of Existing Wells (Task 2.3)
- Evaluation of PDSI Groundwater Sulfate Control System (Task3)
- Groundwater Monitoring Data Report for Second Sampling Event (Task 2.2)
- Results of Numerical Modeling of Sulfate Fate and Transport (Task 4)
- Results of Offsite Well Installation and Testing (Task 2.4)

These task reports address the Aquifer Characterization Report requirements in Section III.C of the MO. The latest information on the plume delineation will be provided in the reports for Tasks 2.2, 2.3, and 2.4, which will contain maps and cross sections showing the distribution of sulfate.

4. IDENTIFICATION OF POTENTIAL INTERIM ACTIONS

An initial task of this work plan will be to identify potential interim actions that can be employed before the Mitigation Plan is completed if: (1) the average sulfate concentration at the point of use in a drinking water supply exceeds 250 mg/L, or (2) if data demonstrate that the average sulfate concentration at the point of use in a drinking water supply will exceed 250 mg/L before the Mitigation Plan is completed. This task will produce a technical memorandum that: (1) identifies how the "average" sulfate concentration will be determined, (2) discusses potential triggers for an interim action, (3) lists specific responses that could be implemented, and (4) describes site-specific factors to be considered when selecting an interim action. As shown by Figure 14, the development of potential interim actions will begin immediately on approval of the work plan so that a planned response is available and can be implemented if needed.

The possible measures to be considered for an interim action will include water treatment, water system operational changes to increase blending, well modifications, and alternative drinking water supplies. The nature of an interim action will depend on site-specific circumstances and could range from small-scale activities, such as providing bottled water or installation of a household point-of-use water treatment system for affected residences, to large-scale actions, such as temporary wellhead treatment at the point-of-entry to a distribution system. The potential interim actions will be identified to a level of detail sufficient for rapid development, if needed. For example, wellhead treatment options, treatment system vendors, treatment unit model numbers, and lead time requirements will be identified to prepare for rapid mobilization.

5. FEASIBILITY STUDY FOR SULFATE MITIGATION PLAN

Pursuant to Section III.D of the MO, PDSI will develop a Mitigation Plan for submittal to ADEQ. The scope of the Mitigation Plan is to practically and cost effectively provide drinking water to owners or operators of a drinking water supply affected by sulfate in excess of 250 mg/L due to the PDSTI.

A FS will be conducted to identify and evaluate mitigation alternatives for the Mitigation Plan. The purpose of the FS is to provide a structured approach for identifying and evaluating the various ways in which mitigation can be accomplished.

The main components of the FS will be:

- Identification and Screening of Mitigation Technologies,
- Development and Screening of Mitigation Alternatives,
- Detailed Analysis of Mitigation Alternatives, and
- Preparation of a Mitigation Plan.

5.1 Identification and Screening of Mitigation Actions and Technologies

The identification and screening of mitigation actions and technologies is a multi-step process identifying mitigation objectives, mitigation actions, mitigation technologies, and process options. Mitigation actions are broad categories of possible actions consisting of one or more mitigation technologies and the process options used by the technologies. A series of screening steps is applied, consisting of criteria such as implementability and effectiveness, to reduce the range of potentially applicable mitigation technologies and process options by eliminating inappropriate or unworkable options. Information developed for the identification of interim actions (Section 4) will be incorporated into the screening as appropriate. Mitigation actions, mitigation technologies, and process options retained by the screening will be assembled into mitigation alternatives for subsequent analysis. Mitigation alternatives are plans that may consist of a single mitigation action or a combination of actions for meeting mitigation objectives.

5.1.1 Mitigation Objectives

Mitigation objectives are qualitative and quantitative goals that meet the requirements of the MO. The constituent of concern is sulfate, an inorganic substance contained in affected groundwater. The MO sets a sulfate level of 250 mg/L for drinking water. Based on the factors identified in the MO, the objective for mitigation is to provide drinking water meeting applicable water quality standards to the owner of a drinking water supply containing sulfate in excess of 250 mg/L due to the PDSTI.

5.1.2 Mitigation Actions

Mitigation actions are generic approaches to mitigation that can be employed singly or in combination to accomplish the mitigation action objectives. A mitigation action can consist of several different technologies and process options. For example, water treatment is a mitigation action that can be used to remove sulfate from drinking water. Water treatment can employ different technologies for removing sulfate such as reverse osmosis, electrodialysis, or nanofiltration. Within each technology there may be several process options that can be used to implement the technology.

For the mitigation of non-hazardous substances such as sulfate, A.R.S. § 49-286 identifies potential mitigation actions as follows:

- Providing an alternative water supply,
- Mixing or blending if economically practicable,
- Economically and technically practicable treatment before ingesting the water, and
- Other mutually agreeable mitigation measures.

The FS will also consider mitigation measures that would control or mitigate sulfate through the application of groundwater/source controls that may include groundwater pumping. Additional mitigation actions to be considered include monitoring of groundwater and drinking water, institutional controls such as restrictions on well drilling, and natural attenuation.

Each mitigation action can employ various technologies depending on site-specific conditions. Alternative water supply can be accomplished by various means including replacement wells, use of an unimpacted supply well, well modification, connection to an existing public water supply, or bottled water. Mixing and blending refers to commingling waters with different sulfate concentrations to meet the numeric mitigation objective. Water treatment would use a physical, chemical, or biological process to remove sulfate and other constituents from drinking water. Depending on the situation, water treatment can be conducted before the point-of-entry to a distribution system using a centralized plant or wellhead treatment system or at the point-of-use with home-based treatment systems.

5.2 Development and Screening of Mitigation Alternatives

Mitigation alternatives will be formulated using mitigation actions, mitigation technologies, and process options retained by the previous screening evaluation. Mitigation alternatives can consist of either a single mitigation action or a combination of mitigation actions that address the mitigation objectives.

For cases in which multiple mitigation technologies or process options are retained by the screening (e.g., reverse osmosis, electrodialysis, and nanofiltration), determination of the most applicable process option will be made based on criteria such as implementability, effectiveness, and cost. PDSI has retained a specialist in water treatment as part of the FS team. Treatability studies will be undertaken at bench and field scale if needed to test the effectiveness of potentially applicable treatment process options and to estimate operational costs.

Mitigation alternatives will be developed in consultation with, and considering the requirements of, local water providers and well owners. Factors to be considered in developing alternatives include projected water needs, infrastructure constraints on water supplies, and water rights. PDSI will retain a water systems engineering firm to evaluate the water needs and delivery infrastructure in the area of the sulfate plume and to provide guidance in the development of mitigation alternatives.

The groundwater fate and transport model (Section 3.5) will be used to develop and evaluate potential plume control response actions. The migration and concentration of sulfate over time will be key factors in evaluating the effectiveness of plume control response actions.

5.3 Detailed Analysis of Mitigation Alternatives

The detailed analysis of mitigation alternatives will evaluate each alternative with respect to its benefits and cost. A.R.S. § 49-286.B indicates that the mitigation selection process shall balance the short-term and long-term public benefits of mitigation with the cost of each alternative, and that only the least costly alternative may be required if more than one alternative satisfies the mitigation objectives. The analysis of alternatives will include consideration of residuals. The estimated quantity and type of residuals created by each alternative will be determined. Means for managing these residuals will be evaluated and included in the feasibility determination and cost estimate.

The mitigation alternatives will then be compared with respect to their benefits and cost. Quantitative estimates of benefits and cost will be developed. The cost analysis will consider direct and indirect capital and the long-term operating costs of each alternative. Costs will be compared based on their 30-year net present value or a similar long-term estimate.

A recommended mitigation alternative or combination of alternatives will be selected using the detailed analysis of alternatives. The recommended mitigation alternative(s) will describe the work to be implemented for the Mitigation Plan.

5.4 Mitigation Plan

The Mitigation Plan will report the results of the alternatives analysis for the FS and will identify the recommended mitigation alternative(s). A schedule for implementation of the recommended alternative(s) will be included in the Mitigation Plan. The plan will also contain a methodology for verification sampling and analysis of drinking water sources to determine

(1) when the average sulfate concentration of a drinking water source exceeds the numeric mitigation objective and (2) whether the sulfate is attributable to the PDSTI. The Mitigation Plan will be submitted to ADEQ for review and approval pursuant to the MO.

6. SCHEDULE

Figure 14 shows a general schedule for implementing the ACP, the identification of interim actions, and the FS for sulfate mitigation. The start of the schedule is the approval of this work plan by ADEQ. Reports identified on Figure 14 will be due on the last day of the month indicated.

The ACP will be implemented immediately on approval of the work plan and a number of tasks can be completed and reported within the first six months. The schedule was developed to complete tasks related to exposure management (e.g., well inventory and identification of potential interim actions) as early as possible and to complete the FS in parallel with the ACP to identify potential mitigation actions as early as possible in the project. However, several tasks will have a long lead time due to the necessity of negotiating access to private and public land to conduct work. For example, the offsite well installation for Task 2.4 could take at least 12 months to permit drill locations on ASLD administered land, although access to some private and public ground may require less lead time. The lead time for Task 2.4 is the critical path item for the ACP. The timing of Task 2.4 impacts the fate and transport modeling for Task 4 which cannot be finalized until the completion of the hydrogeologic characterization.

The identification of potential interim actions will be implemented immediately following approval of the work plan. The objective will be to complete this task within the first four months of the project.

The FS will be conducted in parallel with the ACP. The identification and screening of mitigation technologies, identification and screening of mitigation alternatives, treatability studies, and certain aspects of the detailed analysis of mitigation alternatives will be implemented during the ACP. Completion of the detailed analysis of alternatives requires completion of the sulfate fate and transport evaluation in order to evaluate alternatives using groundwater pumping and completion of treatability studies for evaluating treatment technologies. The Mitigation Plan will be prepared following completion of the detailed analysis of mitigation alternatives.

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