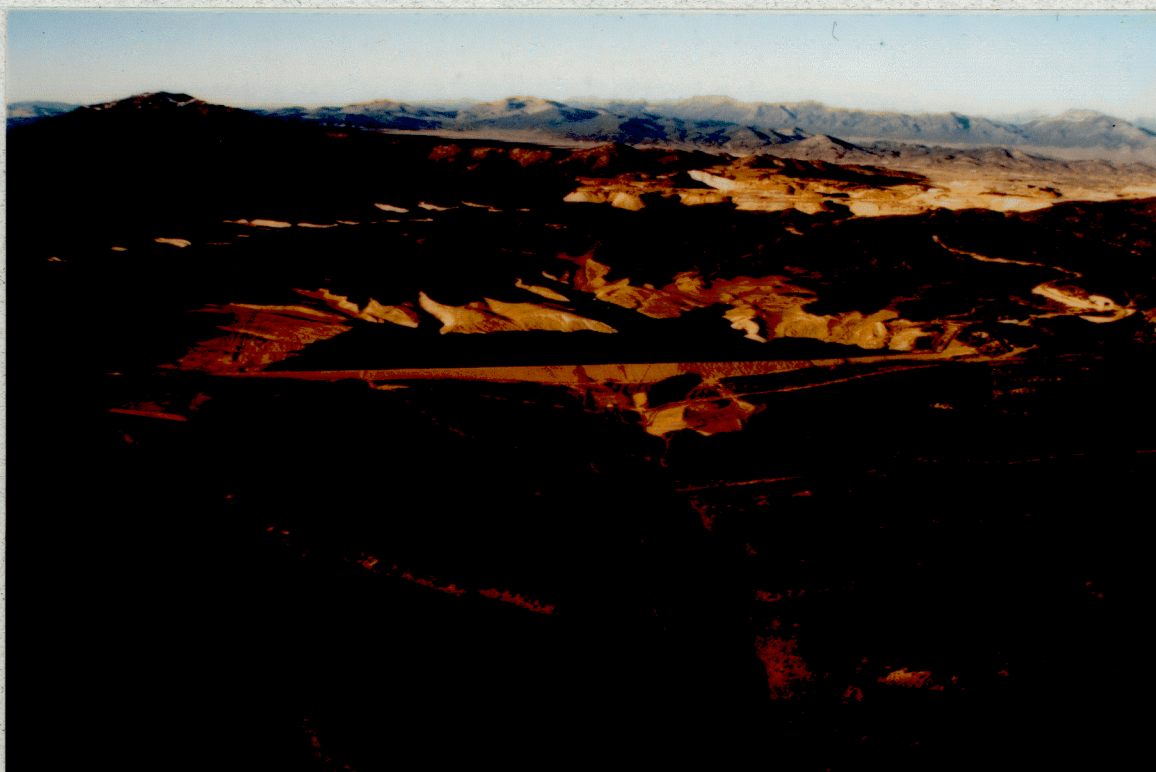



Groundwater Flow and Transport Subregional Model: Giroux Wash Tailings Impoundment



Prepared for:

**Nevada Division of
Environmental Protection**

August 15, 1997


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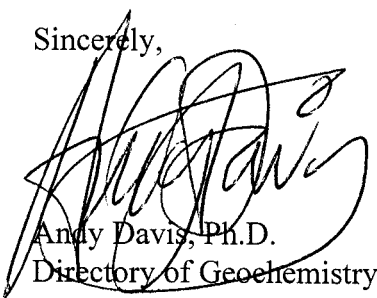
RE: Groundwater Flow and Transport Subregional Model: Giroux Wash Tailings
Impoundment, for BHP Copper-Robinson Operations.

Dear Mr. Drozdoff:

Please find attached the modeling report *Groundwater Flow and Transport Subregional Model: Giroux Wash Tailings Impoundment* that describes the modeling effort and presents results of flow and solute transport simulations from the tailings impoundment. This report was prepared for BHP pursuant to Section 2.9 of the February 27, 1997 *Work Plan—Robinson Operations* that was prepared in accordance with the Consent Agreement between BHP Copper-Robinson Operations and the Nevada Division of Environmental Protection (NDEP).

Please contact me directly with any comments or questions concerning this document at 303/938-8115.

Sincerely,



Andy Davis, Ph.D.

Director of Geochemistry

cc: Ms. Cyndi Byrns, CEM, Environmental Manager, BHP Copper-Robinson
Operations
Ms. Lisa Shevenell, Nevada Bureau of Mines and Geology



Groundwater Flow and Transport Subregional Model: Giroux Wash Tailings Impoundment

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Nevada Division of Environmental Protection

Prepared by:
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for:
BHP Copper - Robinson Operations

August 15, 1997

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Executive Summary

Executive Summary

In accordance with the Consent Agreement between BHP Copper–Robinson Operations and the Nevada Division of Environmental Protection (NDEP), groundwater flow and solute transport modeling was completed for the Giroux Wash Tailings Impoundment. The purpose of conducting this modeling effort was threefold:

- to evaluate tailings water percolation through the unsaturated zone below the impoundment,
- to assess the potential for solute transport and degradation of state waters, and
- to provide an analysis tool for tailings impoundment operation.

A detailed, subregional flow and transport model for the Giroux Wash Tailings Impoundment was constructed by refining the regional model developed for the Environmental Impact Statement (EIS) (PTI 1994). The Giroux Wash Tailings Impoundment model incorporated three well-benchmarked codes:

- HYDRUS_2D for unsaturated zone flow and transport,
- MODFLOW for saturated zone flow,
- MT3D96 for saturated zone transport, and

These three numerical codes were coupled to predict flow and transport through the unsaturated and saturated zones. The subregional impoundment model quantified water flow and solute transport through the vadose zone to groundwater, followed by saturated zone solute transport to the downgradient groundwater compliance point (well WCC-G1). A process flow diagram of how these numerical models were inter-related is shown in Figure 1-3. The model implemented the following conservative flow and solute transport assumptions:

- Seepage will occur over the entire footprint of the impoundment for the operational life of the facility.
- The supernatant pond was assumed to provide an equivalent head across the lateral extent of the impoundment.
- No sorption or retarded transport of solutes will occur.
- The solutes will not be subjected to any chemical reactions.
- Worst-case scenarios for source concentrations were modeled.
- Low permeability soils (i.e., "B" horizon) were not incorporated in the vadose zone model.

The model also accounted for future impoundment development through sequentially increased impoundment surface area and volume.

On the basis of the permitted TDS and solute discharge levels into the impoundment, three tailings disposal cases were evaluated via fate and transport modeling. These cases

simulated varying source concentrations to establish a range of outcomes from the currently observed highest concentrations to progressively worse scenarios:

- Case 1. The highest levels actually observed to date in the solution samples—i.e., TDS = 3,040 mg/L and sulfate = 2,100 mg/L.
- Case 2. A case simulated with higher levels—i.e., TDS = 4,000 mg/L and sulfate = 2,400 mg/L.
- Case 3. A worst case simulation—i.e., TDS = 5,000 mg/L and sulfate = 3,600 mg/L.

The unsaturated zone beneath Giroux Wash extends from the surface of the impoundment to a depth of 750 feet in the western part of the impoundment and to a depth of 250 feet in the eastern part of the impoundment. The variation in water levels is due to a hydraulically sealing fault that trends north-south which acts as an east-west flow barrier. The geologic material beneath the impoundment consists of four main components (Figure 4-1):

- tailings,
- Paleozoic limestone,
- Tertiary sandstone, and
- Quaternary alluvium.

Within the area of investigation groundwater originating in the mountain ranges is encountered at or near the surface and flows south towards the central portion of the White River Valley. Groundwater is first encountered at approximately 250 feet below ground surface (bgs) in the Tertiary Volcanic rocks on the east side of the Giroux Wash Impoundment, whereas groundwater in the Quaternary alluvium on the west side of the impoundment is first encountered at approximately 750 feet bgs. A combination of normal faulting and variation in stratigraphy account for this hydraulic separation across the impoundment.

A series of 40 stress periods (5,000 days each) was run using MT3D96 to simulate sulfate transport from the tailings impoundment area during disposal and post-disposal when the vadose zone was subjected to infiltration of impoundment water. The transport model was then run for an additional 1,096 years at pre-disposal conditions to estimate maximum sulfate concentrations at the point of compliance (POC) well, WCC-G1. Modeling was incorporated to predict flow and transport for more than 1,644 years in the future.

Three scenarios for source solute concentration were simulated. The interpreted results from the solute transport modeling are discussed below.

Case 1, 3,040 mg/L TDS Source

A graph of predicted concentration vs. time for the entire 1,644 year simulation shows sulfate concentrations reaching a maximum of 44 mg/L 750 years in the future at the

41
ES-2

POC well, WCC-G1 (Figure 6-1). Sulfate concentrations are predicted to decrease at the POC well after 1,200 years of transport from the surface source, at which time they begin a return to pre-disposal background concentrations. The estimated TDS concentrations at the POC well reach a maximum of 377 mg/L 750 years from now. A concentration vs. time curve for TDS at the POC well, assuming a 3,040 mg/L source, is shown in Figure 6-2. On the basis of these concentration vs. time curves, it is apparent that sulfate and TDS will not exceed the State of Nevada Drinking Water Standards. *(x mg/L)*
at any time

Case 2, 4,000 mg/L TDS Source

By adjusting these predicted values for a 4,000 mg/L TDS source in the impoundment, the resulting TDS at the POC well will reach maximum concentration of 382 mg/L approximately 750 in the future. Maximum sulfate concentration will occur at the same time as in case one, but is estimated at 44 mg/L. On the basis of these analyses, it is apparent that sulfate and TDS will not exceed the State of Nevada Drinking Water Standards. *years*

Case 3, 5,000 mg/L TDS Source

The same relationship as described above was incorporated to predict TDS concentrations for a 5,000 mg/L source. By adjusting these predicted values for a 5,000 mg/L TDS source in the impoundment, the resulting TDS at the POC well will reach maximum concentration of 387 mg/L approximately 750 in the future. Maximum sulfate concentration will occur at the same time as TDS, but is estimated at 48 mg/L. On the basis of these modeling results, it is apparent that sulfate and TDS once again will not exceed the State of Nevada Drinking Water Standards. *Same as case 1?*

Potential impacts to groundwater quality from these disposal operations are predicted to be minimal. Model results predict no substantial increase in solute concentrations in groundwater at the compliance monitoring point (WCC-G1). Conservative solute transport was assumed in the model input parameters. It will take over 100 years for the infiltration front from the disposed tailings solution to reach the water table on the west side of the facility. On the basis of this unsaturated and saturated zone flow and transport modeling, there will be no impact, above the State of Nevada Drinking Water Standards, to groundwater subjacent to the Giroux Wash Tailings Impoundment at the POC well, WCC-G1. The modeling results support continued operation of the tailings impoundment throughout the remaining mine life of approximately 16 years. *what about on the east side?*

1. Introduction

Pursuant to Section 2.9 of the February 27, 1997, *Work Plan—Robinson Operations*, prepared in accordance with the Consent Agreement between BHP Copper—Robinson Operations and the Nevada Division of Environmental Protection (NDEP), groundwater flow and solute transport modeling has been completed for the Giroux Wash Tailings Impoundment. The purpose of conducting this modeling effort is threefold:

- to evaluate tailings solution percolation through the unsaturated zone below the impoundment,
- to assess the potential for solute transport and degradation of state waters, and
- to provide an analysis tool for tailings impoundment operation.

This report describes the modeling effort and presents results of flow and solute transport simulations from the tailings impoundment, in accordance with Section 2.9.2 of the February 27, 1997, *Work Plan—Robinson Operations*.

The study area is located in the Robinson District south of Ruth, in White Pine County, east-central Nevada (Figure 1-1). This impoundment will ultimately cover an approximate lateral extent of 1,800 acres at the head of the White River Valley, which represents the confluence of White River Wash and Giroux Wash. BHP is disposing of flotation tailings from its mill process into the impoundment at Giroux Wash. At maturity this facility will hold over 200 million tons of tailings. A complete description of the disposal process at Giroux Wash is provided in the *Robinson Project Draft Environmental Impact Statement* (BLM 1994). Previous investigations performed by Welsh Engineering, Inc. (1991), and WESTEC (1994) described the impoundment facility area and provided the initial engineering design for implementation.

Groundwater flow and solute transport modeling for the impoundment was performed in two stages. First, the existing regional groundwater flow model (PTI 1994) developed to support the Environmental Impact Statement (EIS) was updated to incorporate new geologic and hydrogeologic data obtained since BHP began mining in the Robinson District. Next, a more detailed subregional model consistent with the existing regional model was constructed for the Giroux Wash Tailings Impoundment. The EIS regional groundwater flow model (PTI 1994) was originally developed to evaluate

- the potential influence of pumping in the mine area on the regional water table,
- the effects of tailings disposal in Liberty pit on the groundwater system, and
- the flux of water into the open pits after cessation of mining, for the purpose of predicting the water quality in the pit lakes.

Although the regional model was ideal to achieve its objectives, the Giroux Wash Tailings Impoundment model required finer resolution than the regional model could provide. Thus, in the current modeling effort, the regional model provided the basis for

development of a more detailed subregional tailings impoundment model. The Giroux Wash Tailings Impoundment model incorporated the results of three well-benchmarked codes:

- HYDRUS_2D for unsaturated zone flow and transport,
- MODFLOW for saturated zone flow, and
- MT3D for saturated zone solute transport.

The subregional impoundment model quantified water flow and solute transport through the vadose zone to groundwater, followed by saturated zone solute transport to the downgradient groundwater compliance point (well WCC-G1, a monitoring well installed in 1991 south of the impoundment and near the center of the structure [Woodward Clyde 1992]). The model source area for seepage flow included the permitted and operational tailings impoundment and barge-operating channel. The impoundment model implemented a range of tailings solution TDS concentrations (up to 5,000 mg/L). Finally, the model accounted for future development and enlargement of the impoundment as tailings deposition continues throughout the remaining mine life of approximately 16 years.

sealing fault

anticipated

1.1 Objectives of the Investigation

The objective of this investigation was to predict the impact, if any, that mill tailings disposal at the Giroux Wash impoundment may have on water quality of the aquifers potentially affected by the facility. To fulfill this objective, three major tasks were completed:

- the vadose zone infiltration rate and solute flux to the water table was estimated,
- the groundwater flow regimes in the areas adjacent to the impoundment were resolved, and
- the migration of sulfate ions and total dissolved solids (TDS) downgradient of the impoundment were predicted.

1.2 Scope of Work

Groundwater flow models for both the unsaturated and saturated zones were developed to solve the problems posed in Section 1.1. Figure 1-2 is a conceptual flow model of how the several numerical models were incorporated to address both flow and transport problems at the site.

An accurate unsaturated flow and transport model was developed to estimate infiltration and solute flux to the water table through the base of the Giroux Wash impoundment. The finite-element method (FEM) numerical code HYDRUS_2D was used as the approach of choice for solving the unsaturated flow and transport equations because of its proven applicability to a wide variety of field problems (Simunek et al. 1996).

A detailed subregional groundwater model was constructed to evaluate groundwater flow and transport of solutes from the Giroux Wash Tailings Impoundment. A conceptual hydrogeologic model was developed for the site as a basis for construction of the saturated-zone groundwater flow and contaminant transport models. This model included review of all available relevant site data—including boring logs, aquifer test data, climatic data, groundwater elevations, and distribution of contaminants of concern (COCs) in soil and groundwater,—were reviewed.

From the conceptual hydrogeologic model, a steady-state, numerical, groundwater flow model was constructed by using the U.S. Geological Survey (USGS) Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (MODFLOW) (McDonald and Harbaugh 1988). Construction of the model was facilitated by the use of Groundwater Vistas, version 1.88, a graphical pre- and post-processor for use with MODFLOW and MT3D (Rumbaugh 1997).

Transport modeling to determine concentrations of COCs at the point of compliance (POC) was performed with MT3D96 (Zheng 1996). Inputs to the contaminant transport model included

- groundwater flow and heads, obtained from the MODFLOW groundwater flow model, and
- concentrations of COCs that may infiltrate to the water table, as predicted by the HYDRUS_2D unsaturated flow and solute transport model.

Construction of the MT3D input files was also facilitated by the use of Groundwater Vistas.

A process flow diagram of how these numerical models were inter-related is shown in Figure 1-3. Inputs to and outputs from the different models are documented in this diagram.

1.3 Previous Data Acquisition and Analyses

Mobility of solutes in the subsurface underlying the Giroux Wash Tailings Impoundment was examined initially in the site EIS (PTI 1994) and more recently by Geomega (1997a). In addition, the chemical composition of the tailings solution in the impoundment has been monitored monthly since disposal commenced in January 1996. The databases developed during these studies were used in the current evaluation and are summarized below.

1.3.1 The Model for the 1994 EIS

The simulation of flow and transport presented in support of the 1994 EIS incorporated a one-dimensional unsaturated zone model and groundwater flow results taken from the

regional flow model. The main assumptions influencing the solute transport predicted by the 1994 model were

- the average infiltration rate was of 0.004 feet/day,
- the solute transport in the subsurface was conservative (i.e., no chemical reactions or retardation was assumed), and
- sulfate is the analyte of concern for transport modeling.

(Geomega 1997a)
These assumptions were reexamined during the total dissolved solids (TDS) mobility study and during the current modeling effort.

The model used in the 1994 EIS predicted that sulfate concentrations at a downgradient monitoring point (well WCC-G1) will be <250 mg/L and the maximum concentration will reach this location after approximately 900 years (PTI 1994).

1.3.2 Field TDS Mobility Study

(date)
Angle bores from the impoundment embankment collected soil samples from beneath the impoundment in December 1996 (Geomega 1997a). Chemical analyses of these soil samples were used to determine the extent to which the tailings solution had transported solutes into the subsurface material. The fastest-moving solute front measured in these samples had traveled approximately 18 inches during the year between deposition of tailings and soil sampling (0.004 feet/day). The advective flow velocity should decrease following closure of the impoundment because ponded water will no longer be present to drive the infiltration.

what depth?
In addition, bore holes approximately 100 feet south of the impoundment embankment drilled in 1997 failed to encounter groundwater in the impoundment area (Geomega 1997a). These data indicate that potential infiltration from the tailings impoundment, if any, is moving vertically downward and is not flowing laterally.

Another aspect of the 1996 field studies conducted in Giroux Wash was the examination of the hydraulic properties of the upper strata of the regional soil. The B-horizon consists of very fine, clay-sized particles that are present in layers as much as 20 feet thick below the surface of the impoundment area. Column tests demonstrate that this material has a low hydraulic conductivity and acts as a barrier to water infiltration and solute transport (Geomega 1997b). *value?*

1.3.3 Water Chemistry of Tailings Solution and Background Groundwater

The water chemistry of the tailings solution and the background solute concentrations have been measured since tailings disposal commenced. The solute concentrations in the tailings solution were determined from analyses of tailings material recovered from the Repulp House, Pump House, Reclaim Barge, Mill Slurry, entrained impoundment water, and the tailings thickeners. Averages of analytical results of groundwater obtained from

unaffected wells in Giroux Wash (WCC-G1, WCC-G2, WCC-G3, MW-4G, and MW-5G) were used to represent the background solute concentrations. These data were used to determine the solute concentrations that were modeled in this study (Table 1-1).

The average TDS concentration in the 100 samples of the tailings solution was 1,821 mg/L; the maximum TDS concentration was 3,040 mg/L. Sulfate accounted for approximately 60% of the TDS in the tailings solution. Sulfate concentrations in these samples averaged 1,308 mg/L; the maximum sulfate concentration was 2,100 mg/L. The other major TDS component was calcium, which accounted for approximately 27% of the TDS. The average calcium concentration was 604 mg/L; the maximum calcium concentration was 1,400 mg/L.

The average concentrations of the 100 samples do not violate the permitted standards for tailings impoundment operations. However, 41 individual samples exceeded the permitted TDS level (discharge into the impoundment of ≤ 2000 mg/L), and 19 individual samples exceeded the permitted sulfate level (1500 mg/L). The average of 34 background groundwater samples indicated that background TDS in Giroux Wash was 378 mg/L, background sulfate was 30 mg/L, and background calcium was 61 mg/L. *approximately*

On the basis of the permitted TDS and solute discharge levels into the impoundment, three cases were evaluated via fate and transport modeling. These cases simulated varying source concentrations to establish a range of outcomes from the currently observed highest concentrations to progressively worse scenarios:

- Case 1. The highest levels observed to date in the solution samples—i.e., TDS = 3,040 mg/L and sulfate = 2,100 mg/L.
- Case 2. A case simulated with higher levels—i.e., TDS = 4,000 mg/L and sulfate = 2,400 mg/L.
- Case 3. A worst-case simulation—i.e., TDS = 5,000 mg/L and sulfate = 3,000 mg/L.

2. Geologic Description

2.1 Summary

Previous work by a variety of authors described the geology of Robinson Mining District and the Giroux Wash impoundment area. References include Brokaw and Barosh (1968), Einaudi (1982), Fournier (1967), James (1976), Gans and Miller (1983), Hose and Blake (1976), Seedorf (1993), Smith (1976), and Westra (1982). Past consulting investigations that described the geology of the area include Dames & Moore (1982), PTI (1994), Welsh Engineering (1991), WESTEC (1991), and Woodward Clyde (1991, 1992).

As shown in a geologic map of the Giroux Wash area (Figure 2-1) and an east-west hydrogeologic cross section located just south of the dam that forms the basin for the impoundment (Figure 2-2), the stratigraphic section directly underlying the western two thirds of the impoundment consists of a thick deposit of Quaternary alluvium. This alluvial deposit comprises unconsolidated, interbedded gravels, sands, and clays to a depth of more than 1,000 feet, on the basis of boring logs taken just south of the Giroux Wash dam. The Quaternary alluvium is truncated to the east by the first of a series of normal faults.

The eastern third of the impoundment is characterized by a series of normal faults cutting Tertiary volcanic rocks. A north-south cross section through the eastern part of the impoundment area displays geologic strata encountered (Figure 2-3). Within the vadose zone, relatively impermeable Tertiary volcanic rocks, varying from ash flows to rhyolitic lava flows, crop out at the surface outside of the tailings impoundment footprint and dip between 9° and 30° to the west. Near the surface, parts of these formations have been eroded and filled with Tertiary and Quaternary alluvial deposits.

2.2 Detailed Description of the Site Geology (after Welsh 1991)

At the tailings impoundment site, the Paleozoic sedimentary rocks are more than 11,000 feet thick. In stratigraphic order from oldest to youngest, they include the limestones of the Devonian Guilmette Formation, the limestone of the Permian Kaibab Formation, and the siltstone, sandstone, and limestone of the Permian Arcturus Formation. The Kaibab and Arcturus Formations are well exposed in the Egan and Butte Ranges above the valley floor on which the tailings dam is located. In the easternmost part of the site, the Paleozoic rocks are capped by a sequence of Tertiary volcanic rocks that dip 9° to 30° to the west.

The westernmost two thirds of the site is composed of a fault block or "half-graben" structure tilted steeply to the west and filled with Tertiary to Quaternary alluvium; the half-graben is bounded on the west by the Radar Range fault. The easternmost third of the site is composed of small, west-dipping structural blocks separated by steep normal faults. These blocks are composed of Tertiary volcanic rocks overlying Paleozoic strata.

Although the topographically high areas (<8,000 feet) to the east and west of Giroux Wash (about 6,700 feet) represent source areas for the thick alluvium filling the graben, the dominant source area appears to be the mountains (about 8,500 feet) to the west of the site. This interpretation is supported by the fact that to the west of Giroux Wash, the landscape is dominated by a series of coalescing alluvial fans. These fans have pushed the main channels of White River Wash and Giroux Wash (which drain southward and join to form the White River Valley) eastward against fault scarps formed of the west-dipping Tertiary volcanic rocks.

Subsequent to the alluvial filling of the graben was a relatively recent period of stream rejuvenation. The main channel of the White River Wash–Giroux Wash and its major tributaries were incised into the surface of the Tertiary–Quaternary alluvium. The incised channels were then filled with younger silt-sized and fine-sand-sized alluvium.

2.2.1 Stratigraphy

Ten geologic units have been identified at the Giroux Wash site (see Figure 2-1). They are described below from oldest to youngest. Table 2-1 summarizes the stratigraphy, lithology, and average thickness, based on USGS geology maps (Langenheim and Larson 1973).

Pennsylvanian–Permian Sedimentary Rocks, Undivided (Pz)

This unit consists of the Kaibab Limestone, the Arcturus Formation, the Rib Hill Sandstone, the Reipe Spring Limestone, and the Ely Limestone.

- The Kaibab Limestone is a light to medium gray, fine to moderately crystalline massive limestone with indistinct bedding. It contains abundant light brown to gray modular chert.
- The Arcturus Formation is a predominantly yellow to reddish-gray siltstone and fine-grained sandstone interbedded with thin, platy, tan limestone. At the base of the upper unit is a thin evaporite sequence of calcareous siltstone, gypsum, and impure gray limestone. The lower part of the Arcturus Formation consists of a massive, ledge-forming gray limestone, interbedded with sandstone and siltstone.
- The Rib Hill Sandstone is a medium- to fine-grained sandstone and siltstone.
- The Reipe Spring Limestone consists of a medium to gray, finely to moderately crystalline, thin-bedded to massive, bioclastic limestone.
- The Ely Limestone consists of a light olive gray to brownish gray, thin- to thick-bedded cherty limestone.

Tertiary Sheep Pass Formation (Tsp)

This unit consists of a light tan to brown, silty to sandy limestone with sparse gastropod fossils and root casts.

Tertiary Smoky Quartz Rhyolite (Tvf and Tvt)

These are the oldest volcanic rocks in the area. They are typified by phenocrysts of light gray to black smoky quartz. The smoky quartz rhyolite includes both lava flows (Tvf) and unwelded ash-flow tuffs (Tvtu and Tvtl). The rhyolitic lavas range from flow-banded, devitrified, vapor-phase-altered rocks to fresh, vitrophyric, vesiculated, and autobrecciated rocks. The rock contains 30% to 35% phenocrysts of alkali feldspar, clear to smoky quartz, biotite, and rare hornblende in a devitrified glass groundmass. In some areas the formation appears as steep-sided rubbly outcrops of glassy, massive rhyolite.

The ash-flow tuffs range from pink to white and are expressed as rounded or bouldery outcrops mainly in the southern part of the area. The tuffs consist of about 20% crystals, 5% to 30% rock fragments, 5% white pumice, and 45% to 70% devitrified glass groundmass. Lithic fragments consist mainly of devitrified or glassy volcanic rocks with minor sedimentary rocks and rare plutonic lithic fragments. These lithic fragments range from sand-size particles to 5-foot-diameter boulders.

Tertiary Volcaniclastic Sedimentary Rocks (Tvs)

This unit consists of a sequence of tuffaceous sandstone and conglomerate with intercalated ash-flow and ash-fall deposits. The sediments that formed this unit were derived directly from erosion of the underlying ash-flow tuffs. The unit consists of angular to subrounded quartz, feldspar, sparse biotite, and volcanic lithic fragments with variable amounts of devitrified glass groundmass. In places, the sedimentary rocks are hard to distinguish from ash-flow or ash-fall tuffs and may include slightly reworked or even primary tuffs. Most of these rocks, however, display well-developed sedimentary structures—such as bedding, cross-bedding, and conglomerate channels—that indicate deposition in an alluvial-fan or braided-stream environment.

Tertiary Biotite Rhyolite Tuff (Tvb)

This unit consists of platy, locally columnar-jointed, biotite-rich tuff. The rocks range from moderately welded and pumiceous tuff with up to 40% phenocrysts of alkali feldspar, biotite, quartz, and magnetite to unwelded, pumice-rich tuff with 25% to 30% phenocrysts.

Tertiary Crystal-Poor Ash-Flow Tuff (Tva)

Crystal-poor tuff is predominantly tan to brown, with 5% to 20% pumice, 5% to 10% lithic fragments, and 1% to 5% crystals in a fine ash matrix. The pumice is tan to white, unwelded, and silky in appearance. Phenocrysts include sparse quartz, feldspar, and biotite, and lithic fragments are mostly sedimentary or plutonic. Portions are oxidized to a brick red color, perhaps indicating extended subaerial exposure.

Tertiary Alluvium (Ta)

This unit—consisting of poorly cemented calcareous conglomerate and sandstone with minor lacustrine limestone—overlies most of the Tertiary units in the White River Wash–Giroux Wash area. It commonly caps low ridges. Clasts in the conglomerate range up to 15 centimeters across and are subrounded to subangular. The clasts consist of Paleozoic limestone, silicified limestone, hornfels, porphyritic intrusive igneous rocks, and rarer Tertiary volcanic rocks in a calcareous sandy matrix.

Quaternary Alluvial Terraces (Qat)

These materials also consist of poorly sorted sands and gravels similar to the above-described older alluvial materials. However, they were laid down on relatively flat terraces associated with stream deposition during the middle to late Quaternary at a higher base level of erosion.

Older (Tertiary–Quaternary) Alluvium (Qoal₁, Qoal₂, Qoal₃, and Qoal₄)

These materials consist primarily of poorly sorted sands and gravels with a high percentage of cobble-sized clasts. The larger gravel- and cobble-sized clasts vary from rounded to subangular but are predominantly subrounded to subangular, indicating a source for the sediments that was relatively close. The older alluvium unit fills the deep “half-graben” structure located directly east of the Radar Range fault. Active deposition in this west-tilted basin has continued from late Tertiary through late Quaternary time. ←

The numerical sequencing assigned to the older alluvium subunits is less a function of relative age and more a function of geomorphic characteristics. The alluvial deposits designated as Qoal₁ represent the alluvial-fan deposits that form an apron along the mountain front to the west of the site. These deposits are found primarily in the wedge located between the two largest alluvial fans (designated Qoal₂ and Qoal₃) that appear to have been responsible for most of the basin in-filling during the late Quaternary. The Qoal₄ alluvial materials form a relatively thin veneer of pediment gravels and colluvial soils.

Quaternary (Recent) Alluvium (Qal)

These are recent soil materials associated with stream deposition in the entrenched segments of the valley floor. They consist primarily of well-sorted, fine-grained sands and silts.

2.2.2 Tectonism, Volcanism, and Structure

During Tertiary time, there were two major periods of tectonic activity in the study area, which had previously been tectonically quiet. The first, during the late Mesozoic to early Tertiary, resulted in the development of both low- and high-angle thrust faults. However, the most significant activity was the development of a large low-angle thrust fault (or

fault complex) over much of eastern Nevada, structurally known as a decollement. Remnants of a low-angle thrust that may have been associated with this deformation have been mapped across the northernmost and easternmost parts of the tailing dam site. As the trace of this feature is followed southward, it appears to terminate in younger high-angle normal faults with the downthrown side to the east.

Following this Late Cretaceous–early Tertiary crustal shortening, Eocene to Oligocene lacustrine limestones and conglomerates were deposited in shallow depositional basins. Early Oligocene andesitic and rhyolitic lavas and tuffs erupted from isolated vent areas, followed by the eruption of intermediate volcanic rocks coinciding with the onset of the large-scale extension and crustal thinning that formed the Basin and Range structural province.

As much as 250% extensional deformation from middle to late Tertiary time has produced the Basin and Range horst-and-graben structure that dominates the landscape today. The horsts are represented by the north-trending, elongate mountain ranges, and the grabens form the intervening, wide, flat-bottomed valleys filled with deep alluvium deposits.

The early crustal thinning was accompanied by extensive volcanic activity. Although most volcanism in east-central Nevada had reached quiescence by early to middle Miocene time, extension continues to the present, as evidenced by multiple generations of imbricate normal faults, the youngest of which cut late Tertiary and Quaternary conglomerate and lacustrine valley-fill deposits.

On this site, tilting of the Paleozoic to lower Tertiary section ranges from 9° to 30° to the west. Dips in the youngest Tertiary sedimentary rocks are shallower, consistent with syndepositional growth faulting along the Radar Ridge fault to the west. To the east, several north-trending, downthrown blocks, which possibly represent two generations of normal faulting, are inferred to cut the Tertiary sequence but do not appear to disturb Quaternary alluvium or older (Tertiary–Quaternary) alluvium and, hence, do not affect the foundation of the impoundment.

3. Hydrogeologic Description

The hydrogeology of the Giroux Wash area has been included as part of various regional and local hydrogeologic investigations.

3.1 Regional Hydrogeology

A description of the regional hydrogeology documented in previous investigations (e.g., PTI 1994) performed for the Robinson District is included in this section of the report. ←

The Giroux Wash area is located in the Carbonate-Rock hydrologic province of the Great Basin, as defined by Burbey and Prudic (1991), which covers approximately the eastern half of Nevada. Groundwater in this region occurs in two hydrologic regimes: alluvial sediments filling the basins or valleys between the high ranges, and Paleozoic rocks that are exposed within the mountain ranges and dip beneath the alluvial sediments of the basins.

Water moves from the mountain ranges by surface flow in streams, evaporation, plant transpiration and by subsurface flow through the aquifers. Groundwater through-put within the regional aquifers is controlled by localized hydraulic features that result from primary (rock matrix) and secondary diagenetic processes.

Water is lost from the basins by evaporation, plant transpiration, and by surface water flow via streams out of the basins. Water is also lost from the shallower alluvial aquifers to the deeper Paleozoic rock system by flow out of one region and into another. There is variable inter-basin hydrogeologic communication throughout the regional groundwater system.

In the study area, the main ridge of the Egan Range is believed to be a major divide, not only for surface water but also for the groundwater systems (Figure 1-1). On the west side of this divide (e.g., Jakes Valley, White River Valley), the regional flow is south toward the Colorado River Basin, whereas on the east side of the divide, the regional system flows northeast toward the Great Salt Desert.

Hydraulic heads are generally lower in the deeper Paleozoic rocks than in the overlying alluvial aquifers, indicating that the Robinson District is an area of groundwater recharge, which comes principally from precipitation in the mountain ranges (Thomas et al. 1986). Precipitation is strongly correlated to elevation, ranging from 6 inches/year in the valleys to more than 20 inches/year in the surrounding mountains. Snowmelt recharges the Paleozoic rocks directly, and surface flow down mountain streams reaches the alluvial valleys and descends into the coarse alluvium along the mountain fronts to recharge the alluvial aquifers. Direct rainfall also contributes to recharge in both aquifer systems.

The percentage of precipitation and runoff that reaches groundwater varies, from a regional average of 5% for the Paleozoic rocks (Burbey and Prudic 1991) to local values as high as 25% (5 inches/year) for the mountainous areas of White Pine County (Maxey and Eakin 1949). There is a net groundwater discharge in some valley-bottoms areas (e.g., Steptoe Valley near McGill) where evaporation and transpiration losses from shallow groundwater exceed annual precipitation rates (Bedinger et al. 1984).

3.2 Local Hydrogeology

Primary aquifers in the Giroux Wash area consist of the Paleozoic rocks and the Quaternary alluvial basin-fill deposits. These strata range widely across a broad spectrum of gross thickness, lithology, and hydraulic properties.

3.2.1 Paleozoic Rocks

Paleozoic bedrock aquifers can vary locally from unconfined or confined, depending on topography and degree of burial. At higher elevations where meteoric water recharges the systems, these aquifers are unconfined. In the basins (valleys) where the Paleozoic rocks dip below other strata, they act as confined aquifers.

Groundwater flux through the Paleozoic rock sequences is determined by localized hydraulic features within their gross thickness. Formation of conductive flow units is controlled by both primary and secondary hydraulic features including fracture development, original matrix porosity, and secondary diagenetic features (both dissolution and mineralization). These primary and secondary geohydraulic features contribute to the average hydraulic conductivity of individual flow units within these rocks. Thickness of the preferential flow units determines their ability to transmit groundwater flow to adjacent hydrostratigraphic units. Hydraulic conductivity within these rock types varies over several orders of magnitude, depending on the formation of secondary features. ←

3.2.2 Alluvial Aquifers

Alluvial aquifers in the area are typically unconfined. Thickness of these strata varies depending on spatial positioning within the basin proper. At the edge of the valleys, the alluvial deposits are thinner than in the center of the basin; more than 1,000 feet of alluvial material was encountered in monitoring well WCC-G1, just south of the Giroux Wash Tailings Impoundment.

Hydraulic conductivity of these alluvial deposits varies ^{over} several orders of magnitude. Higher conductivity is encountered near the center of the basins, as corroborated by aquifer testing in Steptoe Valley (PTI 1994). Besides location, particle size distribution, degree of sorting, and amount of secondary alteration also determine the hydraulic conductivity of this hydrostratigraphic unit.

3.2.3 Fault Disruption of Aquifers

The north-trending faults that cross the tailings impoundment area and bound bedrock blocks form hydraulically significant barriers to groundwater flow. Either these faults act as flow barriers themselves, or movement along them has juxtaposed lower-conductivity volcanic rocks against higher-conductivity alluvial strata. There is more than 500 feet of head difference between monitoring wells WCC-G1 and WCC-G3. ~~The latter is~~ *which are* approximately 4,500 feet to the east of WCC-G1. *apart*

This faulting separates the groundwater system on the western part of the Giroux Wash impoundment from that of the eastern part. Outcropping strata in the western part are unconsolidated Quaternary alluvium, whereas those on the eastern part are Tertiary volcanic rocks and unconsolidated alluvial sediments.

3.3 Summary Description of Groundwater Occurrence and Movement

On the west side of the Egan Range, groundwater and surface water generally flow south, toward the Colorado River Basin. Groundwater originating in the mountain ranges is encountered at or near the surface, and it flows toward the axis of the White River Valley as it makes its way south. Groundwater is encountered at greater depths in the basins. Figure 3-1 is a water table map for the study area; ~~the map is~~ *←* based on the monitoring wells rimming the impoundment as well as USGS maps (Thomas et al. 1986). Heads are higher to the north, east, and west than in the White River Valley. Hydraulic gradients are typically steeper in the area surrounding the valley because of greater recharge and generally lower hydraulic conductivity. Gradients become flatter farther south and in the center of the valley. Hydraulic heads are usually lower in the deeper Paleozoic rocks; therefore, the shallower alluvial aquifers function as a source of groundwater recharge *for* ~~to~~ the regional aquifers.

Groundwater in the Tertiary volcanic rocks on the east side of the Giroux Wash impoundment is first encountered at approximately 250 feet below ground surface (bgs), whereas groundwater in the Quaternary alluvium on the west side of the impoundment is encountered at approximately 750 feet bgs. A combination of normal faulting and variation in stratigraphy account for this hydraulic separation across the impoundment. Groundwater flow is southward from the tailings impoundment toward the axis of the White River Valley.

4. Vadose Zone Flow and Solute Transport

The focus of this part of the study is to determine the analyte concentrations in water infiltrating from the tailings impoundment in Giroux Wash to the water table. The depth to groundwater varies between 250 feet on the eastern side to approximately 750 feet on the western side of the impoundment. Because of these distances and the concomitant long period of time needed for water to move from the impoundment to the water table, practical assessment of the infiltrating water requires that the infiltration be modeled.

4.1 Vadose Zone Description

In the western part of Giroux Wash, the unsaturated zone extends from the surface to a depth of approximately 750 feet bgs. In the eastern part of the wash, it extends to approximately 250 feet bgs. This variation in water levels is due to a fault running parallel to the axis of the wash, which acts as an east-west flow barrier. The material in the wash consists of tailings, Paleozoic limestone, Tertiary sandstone, and Quaternary alluvium (Figure 4-1).

4.1.1 Tailings Material

The tailings material consists of fine-grained particles that currently cover the existing impoundment footprint to depths of ≤ 50 feet. The extent of the impoundment coverage changes during its life. Initially, the tailings were deposited along the impoundment embankment; additional areas north of the embankment will be covered during filling. The elevation to which the impoundment will fill can be expressed as a temporal empirical function (SRK 1997), i.e.,

$$E = 0.0259t + 6695, \quad (4-1)$$

where

E is the contour elevation and

t is the time in days since January 1, 1996.

Hydraulically, the fine tailings have a relatively low saturated conductivity (1×10^{-6} cm/s) and a saturated water content equivalent to the porosity (0.30; PTI 1994). These parameters were used to determine the infiltration rate from the saturated tailings (section 4.4.1).

4.1.2 Paleozoic Limestone

The Paleozoic limestone (part of map unit Pz; Figure 2-1) crops out along the extreme east and west edges of the wash. The limestone dips from both sides toward the center of the wash, forming the "trough" below the other materials. Because of uplift of blocks

along the series of north-trending faults (see Figure 2-2), the limestone is only 100 feet below the tailings impoundment at its eastern edge but is more than 1,000 feet below the impoundment in the middle and western parts of the wash.

Unsaturated flow through the limestone is limited by the relatively low saturated conductivity of the material (10^{-5} cm/s) and the low porosity (0.08) and residual water content (0.04) (WESTEC 1991, PTI 1994). The conductivity value reported here is probably representative of the effective porosity of the material where water flow is occurring primarily in fractures.

4.1.3 Tertiary Sandstone

The Tertiary sandstone (part of map unit Tvs; Figure 2-1) overlies the limestone across the breadth of the wash. Because of block faulting, the sandstone is as shallow as 10 feet beneath the ground surface on the east side of the wash, reaches a depth of >1,000 feet in the middle of the wash, and occurs at a depth of 200 feet on the western edge. The tailings impoundment does not cover the sandstone surface exposure, which occurs adjacent to the limestone exposure on the eastern edge of the wash.

Unsaturated flow through the sandstone is limited by the relatively low saturated conductivity (5×10^{-5} cm/s), porosity (0.08), and residual water content (0.04) of the material (WESTEC 1991, PTI 1994). The conductivity value is probably representative of the effective porosity of the material through which water flows primarily in fractures.

4.1.4 Quaternary Alluvium

The alluvium fill, the source of which is the adjacent ranges, is approximately 1,000 feet thick at its deepest point in the middle of the wash. All parts of the tailings impoundment are underlain by at least 10 feet of alluvium, and the alluvium reaches from the ground surface to the water table across most of the wash.

Most of the unsaturated flow in the wash occurs in the alluvium, which is more conductive (up to 10^{-2} cm/s) and has greater porosity (0.25) and residual water content (0.07) compared to the bedrock (WESTEC 1991, PTI 1994). Assuming a saturated conductivity value of 10^{-2} cm/s (28.5 feet/day) for the alluvium is a conservative estimate of the true conductivity, given the impermeable nature of the contained B-horizon layers (Geomega 1997b).

4.2 Infiltration Modeling

Infiltration was modeled by using the numerical code HYDRUS_2D (Simunek et al. 1996). HYDRUS_2D is an updated version of SWMS_2D, a well-documented and well-benchmarked U.S. Department of Agriculture computer code that uses a finite-element approach to simulate groundwater flow and solute transport in the unsaturated zone. HYDRUS_2D solves a finite-element analogue of well-established, governing flow and

transport equations in two dimensions. HYDRUS_2D outputs moisture profiles in the soil at time intervals designated by the user.

The partial differential equation for groundwater flow is Richards equation, a nonlinear partial differential equation based on mass conservation that models water flow in the unsaturated zone of the subsurface:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial z} \left[K_{zz} \left(\frac{\partial h}{\partial z} - 1 \right) \right] = S \frac{\partial h}{\partial t}, \quad (4-2)$$

where

K_{xx} and K_{zz} are hydraulic conductivity values along the lateral (x) and vertical (z) axes [L/T],

h is the potentiometric head [L],

S is the specific storage of the porous material [L^{-1}],

t is time [T].

The complexity of physical unsaturated zone flow systems makes modeling them with a tractable set of equations difficult. The computer-based, numerical approaches required to solve these equations add another level of complexity and often entail prohibitive run times. Therefore, to formulate a manageable model, assumptions and approximations that simplify the physical system were required. These assumptions include

- groundwater flow is laminar;
- groundwater is homogeneous, isothermal, and incompressible; and
- the physical parameters do not change with the system's state (e.g., porosity of vadose zone will not vary with variation in unrelated parameters such as TDS).

These assumptions are reasonable for application to the unsaturated zone in Giroux Wash, as the flow rate is slow enough that turbulence is unlikely to occur and ambient climatic conditions do not alter the state of water in the subsurface (e.g., groundwater will not freeze and thaw at depth).

The partial differential equation for contaminant fate and transport modeling is the advective dispersion equation:

$$\frac{\partial}{\partial x} \left(D_{xx} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial z} \left(D_{zz} \frac{\partial c}{\partial z} \right) - q_x \frac{\partial c}{\partial x} - q_z \frac{\partial c}{\partial z} - \lambda_w c - \frac{\lambda_s \rho_b K_d}{\theta} s = \frac{\partial c}{\partial t} + \frac{\rho_b K_d}{\theta} \frac{\partial s}{\partial t}, \quad (4-3)$$

where

D_{xx} and D_{zz} are dispersion coefficients along the lateral (x) and vertical (z) axes,

q_x and q_z are advective velocities of the groundwater along the lateral and vertical axes,
 λ_s and λ_w are the soil and groundwater decay rates of contaminants,
 ρ_b is the bulk density of the soil,
 K_d is the adsorption partitioning coefficient,
 θ is the water content,
 c is the contaminant concentration in groundwater, and
 s is the contaminant concentration sorbed to the soil.

4.3 Conditions Assumed in the Infiltration Model

The Giroux Wash Tailings Impoundment model separates the wash into two zones: the region covered by the final tailings impoundment footprint and the region where no tailings will be deposited (Figure 4-2). The covered and uncovered regions allow very different volumes of water to infiltrate through their surfaces.

Infiltration in the uncovered region is dominated by the negative water balance at the site, which experiences a net evaporation of 48 inches/year. Thus, the limited precipitation (about 10 in/year) on the uncovered region is insufficient to wet the Giroux Wash subsurface and result in significant percolation downward several hundred feet to recharge the water table. For this reason the model assumes that there is no percolation through the uncovered region. This assumption is conservative because any percolation through this region would serve to dilute solute concentrations percolating through the region covered by the impoundment.

The region covered by tailings experiences the same evaporative effects; however, the tailings deposition in the form of a slurry provides adequate water to keep the water content of the tailings relatively high. In addition, the ponded water in the impoundment provides a driving force for percolation into the local subsurface that exceeds the evaporative force.

Given these facts, infiltration beyond the ambient recharge (if any) is assumed to occur only in the part of the wash covered by tailings. The percolation through the impoundment area takes place at differing rates depending on the conditions in the impoundment. As the impoundment began to fill, saturated tailings were disposed of immediately behind the impoundment dam while the northern area of the wash remained uncovered. As the area behind the dam filled with tailings, the extent of the saturated zone expanded northward. The tailings will eventually reach the maximum elevation described by equation 4-1, which expresses the elevation of the tailings in the impoundment as a function of time in order to calculate the period that subsurface soils are in contact with saturated tailings. This model conservatively assumes that the entirety of the impoundment is covered for the operating lifetime of the impoundment.

Saturated tailings are assumed to transmit both moisture and solutes to the subsurface soils from the time the tailings cover the soil until they reach the water table. During this time, the tailings are assumed to remain saturated by tailings solution with constant solute concentrations. Following closure, the water source for the tailings is removed, and the water in the tailings drains down into the subsurface or evaporates because of the ambient precipitation and evaporation conditions. The solute concentrations in the drain-down water are assumed to equal those of the tailings solution. Recharging precipitation entering the top surface of the impoundment is assumed to have solute concentrations equivalent to background groundwater.

Mathematically, the relationship between the concentration of solutes and their advection and dispersion is termed "linear" (equation 4-3). This relationship means that an increase in the initial concentration of a given solute will result in a proportional increase in the predicted concentration of that solute when the infiltrating water reaches the water table. For example, if equation 4-3 predicts that an initial tailings solution concentration of 100 mg/L will be reduced during infiltration to 25 mg/L at the level of the water table, then an initial concentration of 1,000 mg/L would result in a predicted concentration of 250 mg/L (i.e., both the input and predicted result are scaled by the same factor of 10). Therefore, model predictions for the investigated range of initial solute concentrations can be determined from the results presented here (Appendix B) by proportionally rescaling the input and predicted concentrations.

On the basis of data from bore holes, water flow in the Giroux Wash unsaturated zone is assumed to be primarily vertical for the purpose of modeling. In the infiltration model, the water flow occurs in two-dimensional, east-west cross sections of the valley. In actuality, the trough-shaped body of alluvium filling the valley probably contains lateral unsaturated groundwater flow moving toward the center of the trough because of the contact between the permeable alluvium and the less permeable bedrock. In the north-south direction, the contact slopes comparatively slightly (<2%; WESTEC 1991).

4.4 Model Parameters

The parameters to be assigned to conduct the vadose zone model are recharge rate, hydraulic properties, solute transport properties, and depth to groundwater. (see Table 4-1). Conservative estimates of parameter values were employed when direct measurements were unavailable, and a sensitivity analysis was conducted on the model (Section 4.5)

4.4.1 Recharge Rate

Recharge to groundwater from the impoundment area is due to infiltration of tailings solution and precipitation, tempered by evaporation. A conservative estimate of net *infiltration* recharge (0.008 feet/day) was based on a value double the maximum observed rate (0.004 feet/day). This assumed infiltration rate is in good agreement with the rate conservatively estimated from the hydraulic conductivity of the tailings (10^{-6} cm/s) (PTI 1994), the

hydraulic head (5 feet) expected in the tailings pond (SRK 1997), and the annual precipitation and evaporation expected in the impoundment (SRK 1997). The 5 feet corresponds to the average head occurring when the supernatant pond is lying directly over a segment of the impoundment. This hydraulic head is applied across the entire impoundment area resulting in an overestimate of seepage from the areas not beneath the supernatant pond where a hydraulic head of 1 foot was estimated (SRK 1997). The rate of advance of the seepage front, q , from tailings solution infiltration is calculated by

$$q = K_{\text{sat}} H = 2.76 \times 10^{-3} \text{ feet / day} \times 5 = 1.38 \times 10^{-2} \text{ feet / day} , \quad (4-4)$$

where

K_{sat} is saturated permeability and
 H is average head.

The net evaporation rate, E_n , is 1.1×10^{-2} feet/day at the surface of the impoundment. However, using the evaporation rate defined at the surface of the tailings overestimates the rate of evaporation at depth within the tailings. Assuming that evaporation rate linearly decreases from a maximum at the surface of the tailings to zero at a depth of 10 feet (Maurer 1996), the average evaporation rate in the tailings is approximately 6×10^{-3} feet/day. Hence, the infiltration rate, I , will be approximately 0.0078 feet/day. This infiltration rate is approximately double the rate used in the previous modeling effort (PTI 1994) and agrees well with the rate assumed for this investigation.

Following the closure of the impoundment, the model assumes a recharge rate of 6.6×10^{-4} feet/day, which is consistent with the assumed recharge of the saturated zone model (see Section 5). This assumption is conservative given the negative water balance of the area and the relatively low permeability of the tailings and B-horizon soils that limit infiltration. Hydrogeologic evaluations of the possibility of recharge to deep aquifers in other areas of Nevada have concluded that there is actually extremely limited recharge to deep groundwater through valley-floor alluvium (Zones 1961).

4.4.2 Hydraulic Properties of the Wash Materials

Hydraulic properties (e.g., saturated conductivity, porosity, and residual water content) of the alluvium, sandstone, and limestone were determined from the geotechnical study performed for construction of the impoundment (WESTEC 1991, PTI 1994) (Table 4-1). The unsaturated model requires selection of van Genuchten curve-fitting parameters to define the conductivity of the materials as a function their water content (Table 4-1). The curve-fitting parameters were inferred from the saturated conductivity values by using parameter values reported in the literature for materials with similar conductivities.

For the modeling purposes, flow in the sandstone and limestone bedrock units was treated as flow in porous media rather than fracture-controlled flow. The hydraulic parameter values used for these units represent the effective properties of the media.

4.4.3 Solute Transport Properties

Solute transport parameters used in the model were obtained from site-specific field observations and conservative estimates of the unsaturated zone properties (Table 4-2).

Solute adsorption and precipitation were observed during the field TDS mobility study (Geomega 1997a). During the study, the solute front in the bore hole samples taken from the impoundment embankment infiltrated approximately half the distance of the wetting front. This result corresponds to a retardation factor of $R = 2$ and a sorption partitioning coefficient of $K_d = 0.16$. In addition, material recovered from the subsurface showed evidence of calcite precipitation on soil grains. Calcium accounts for approximately 27% of the TDS present in the tailings solution, which is supersaturated with respect to calcite. Therefore, TDS concentrations will probably be reduced in the subsurface owing to precipitation of calcite and other minerals from solution.

Despite the above results, the modeled transport of solutes in the Giroux Wash unsaturated zone assumed that the solutes do not participate in any chemical reactions. This solute transport assumption represents a conservative evaluation of the transport mechanisms in the subsurface (e.g., transport without solute retardation or reaction).

The rate of diffusion and dispersion of solutes through the Giroux Wash subsurface was taken to be 20 cm²/day in the alluvium and 10 cm²/day in the bedrock. These values were based on the upper bound of typical dispersion rates in permeable and impermeable soil materials (Jury 1991).

4.4.4 Depth to Groundwater

The depth to groundwater was determined from the steady-state conditions in the wash prior to infiltration through the impoundment (Figure 4-1). The depth to groundwater beneath the impoundment varies: the maximum depth of 750 feet occurs under the west side of the impoundment, and the minimum depth of 250 occurs under the east side. The water table is simulated in the model by fixing the head in the finite elements located at that depth to zero.

4.5 Model Discretization

Numerical discretization divided the Giroux Wash impoundment into 50,694 finite elements.

- Each of 14 horizontal layers (*rows*) was divided into 51 *slices* (along the east-west direction) and 71 *columns* (along the north-south direction).

- Each slice and each column were 200 feet wide. They formed a grid of 200 foot \times 200 foot squares that was coincident with the impoundment area (Figure 4-2).
- In the vertical dimension (Figure 4-3), a slice through the subsurface was discretized into 14 rows of unequal thickness as well as the 71 uniform-width columns. The rows near the top of the model domain are thinner than those at depth. The spacing of the rows increases with depth to a maximum of 75 feet at the water table.

The top of the model domain represents the surface of the tailings impoundment. In map view, each of the 200 foot \times 200 foot two-dimensional squares in each row correlates with a corresponding three-dimensional cell in the groundwater flow model. Thus it is possible to accurately predict the wetting and solute fronts as they move downward from element to element, i.e., from the vadose zone into the water table.

Each model element is assigned hydraulic and transport properties based on the subsurface material found at that element's location. The discretized subsurface geology of Giroux Wash (Figure 4-4) features alluvium throughout most of the model domain on the west side and volcanic rocks on the east side with Paleozoic sedimentary rock on the edges.

4.6 Initial Conditions

The initial conditions for the unsaturated zone model were designed to approximate the conditions in Giroux Wash prior to the disposal of tailings (i.e., the pre-1996 conditions). The modeled subsurface material has a residual moisture content consistent with a chemical composition identical to background groundwater.

4.7 Boundary Conditions

The bottom boundary condition of the unsaturated zone model fixes the hydraulic head of those elements to zero to represent the saturated condition at the water table.

The surface boundary condition is a variable flux condition that accounts for seepage from the impoundment during its operation, followed by a period of drain down and drying after closure during which the infiltration rate decreases.

The side boundaries of the model domain are free drainage boundaries that would allow water and solutes to move through the sides of the model domain if flow were to extend laterally to that distance. However, the side boundaries were taken sufficiently far from the flow areas that flow and solute transport do not reach the boundaries, and so the choice of boundary conditions for the lateral boundaries was inconsequential.

4.8 Model Results: Rates of Infiltration and Solute Transport

The model predictions conserved mass for both the water and the solutes in the Giroux Wash unsaturated zones. Both the water mass balance and the solute mass balance had errors of less than 1%.

Initially, solutes are transported downward from the surface at a relatively rapid rate under the driving force of the ponded tailings solution. Under these conditions, the solute front propagates approximately 231 feet during the 16 years of impoundment operation (Figures 4-5 through 4-7). The movement rate of the solute front decreases gradually over the next 20 years after closure of the impoundment while the tailings drain under the influence of gravity and ambient precipitation and evaporation without constant recharge by additional tailings solution. After the impoundment drains, the solute front propagates relatively slowly, as the sole remaining driving forces are

- the limited infiltration of precipitation under ambient conditions and
- dispersion, which has a significant impact on solute mobility at this low advective velocity.

The solute concentrations reaching the water table range up to 33% of the original concentration in the tailings solution. This maximum concentration is predicted in the shallower water table on the ~~the~~ solutes are completely flushed from the subsurface by precipitation recharge and dispersion after approximately 550 years (Figure 4-8). Infiltration is fastest in the alluvium-filled part of the wash, especially near the contact between alluvium and bedrock where water preferentially flows in the more permeable alluvium (Figure 4-9). However, the predicted infiltration reaches groundwater in the bedrock on the east side of the impoundment sooner because the groundwater in that area is more than 500 feet closer to the surface. *east or west side?*

Solute transport takes place at comparable speeds in the bedrock and alluvium, moving fastest along the alluvium-bedrock interface. The lower porosity of the bedrock units allows solute transport at a rate comparable to that in the alluvium, as advective velocity is inversely proportional to porosity, i.e., *when*

$$q_a = \frac{i}{\phi}, \quad (4-8)$$

where

q_a is the advective velocity,
 i is the flow velocity, and
 ϕ is the porosity.

X mg/L SO4
TDS

The maximum solute concentration reaches the water table in the bedrock on the east side of the impoundment because of the shallower depth to groundwater in that area.

4.9 Sensitivity Analysis

Conservative parameter values were assumed when site-specific data was not available for the entirety of the model domain. Many of these assumptions (alluvial saturated conductivity, chemical adsorption, chemical reactivity, etc.) represent the conservative bound of appropriate parameter choices, indicating that any sensitivity evaluation of these parameters would result in a prediction where less solute is transported to the water table.

Overall, the most important parameter in predicting transport is the recharge rate (Section 4.4.1). The recharge rates (both during operation and after closure) were doubled to determine model sensitivity due to variability in this parameter. Transport from doubling the recharge rate resulted in an approximately two-fold increase in predicted transport speed but only a slight increase in predicted solute concentrations (Figure 4-10). Conversely, when the modeled operating recharge rate was retained and the postclosure recharge rate was reduced to zero, as suggested by Zones (1961), predicted infiltration in the impoundment area was insufficient to transport solutes to the water table.

5. Groundwater Flow Modeling

conducted

Groundwater flow modeling of the saturated zone was completed to continue the unsaturated zone modeling to complete flow through the aquifers beneath Giroux Wash. A numerical model was constructed to quantify the groundwater flow down from the mountain ranges that border the impoundment on three sides and out toward the center of White River Valley. Vertical flow from the shallower basin-fill aquifers into the deeper aquifers was also resolved by modeling. The following sections describe this model development from conceptualization to simulated predictions.

5.1 Conceptual Flow Model

Regional groundwater flow is generally toward the south, away from the impoundment area, and it is controlled by several factors. The Giroux Wash model domain is shown on the USGS regional water table map (Figure 5-1; Thomas et al. 1986).

5.1.1 Inflow of Groundwater into the Model Domain

Groundwater flows from the mountains, through the alluvial fans along the sides of the valleys, and into the alluvial aquifers of the valleys. There is groundwater flux into the White River Valley from the Jakes Valley, located just to the northwest. General groundwater flow in the valleys tends to parallel the strike of the valley, flowing to the south in White River Valley.

The mountain ranges adjacent to the Giroux Wash function as regional hydrologic divides for surface and groundwater.

- The Egan Range appears to be a major regional groundwater divide for both the shallow and deeper systems on the east side of the White River Valley. These mountains are interpreted to act as a major water divide separating groundwater on the east, flowing northeast toward the Great Salt Lake, from water on the west side, which flows south toward the Colorado River.
- The White Pine and Grant Ranges form the western boundary of the White River Valley. It is interpreted that these mountain ranges function as water divides on the west side of the White River Valley.
- The Jakes Valley, just northwest of the White River Valley, is separated from the White River Valley by a northeast-trending ridge that is part of the Horse Range. It is interpreted that this ridge acts as a semiconductive hydraulic barrier, allowing flow into the White River Valley (Thomas et al. 1986).

Rainfall originating at higher elevations in the ranges surrounding the tailings impoundment is the source for groundwater in the alluvial basin (valley) south of the facility. This meteoric water infiltrates through the vadose zone and recharges the

groundwater aquifers in the area. Evapotranspiration is higher in the valleys than in the mountains and has a major impact on groundwater recharge.

5.1.2 Groundwater Flow Beneath the Impoundment Site

Faulting and relatively impermeable volcanic rocks—expressed at the surface on the east side of the White River Valley and the Giroux Wash impoundment area—create hydraulic barriers that complicate the pattern of groundwater flow. These barriers cause groundwater to be encountered at 250 feet bgs in the alluvium and volcanic rocks on the east side of the valley, whereas it occurs at approximately 750 feet bgs on the west side in alluvial sediments.

A pair of schematic cross sections displays groundwater flow, occurrence of groundwater, and geology across the Giroux Wash area (Figures 5-2 and 5-3). Figure 3-1, a water table map constructed from water-level measurements taken during the first quarter of 1997 and regional data, shows flow generally southward from the impoundment. There is also a large discontinuity in heads across the Giroux Wash fault, with water on the east (downthrown) side being about 500 feet higher than on the west side.

5.1.2.1 Effect of Normal Faulting

A fault may act as a hydrologic barrier or as a hydrologic conduit or may have no influence on groundwater flow. Hydrologic data from which fault behavior can be inferred are limited in the Giroux Wash area. On the basis of available data, major faults within the model domain were identified and were included in the groundwater model if they appeared to influence groundwater flow. Normal faults in the area form hydraulic barriers to flow, as determined by water-level data.

- Groundwater was encountered at 750 feet bgs in monitoring well WCC-1.
- The water table is interpreted to occur 250 to 300 feet bgs on the east side of the valley where the volcanic rocks are nearer to the surface.
- Monitoring well WCC-3, located 4,500 feet east of WCC-G1, encountered water at 510 feet bgs, and it reached an equilibrium water depth of 250 feet bgs after one month.

5.1.2.2 Effect of Volcanic Rocks vs. Alluvium

The preponderance of volcanic rocks on the east side of the valley may also influence the depth to groundwater in the area. These lower-conductivity rocks impede flow laterally and vertically, resulting in higher water table elevations.

Volcanic rocks crop out in a band several thousand feet wide along the western edge of White River Valley, and they are interpreted to terminate about 1 mile south of the Giroux Wash embankment. These Tertiary volcanic flows dip about 9° to 30° to the southwest. It appears that igneous intrusions are related to the extensional forces that created the north-trending normal-faulting regime on the eastern side of the White River Valley.

The Tertiary volcanic rocks tend to have substantially lower hydraulic conductivities than their Tertiary sedimentary counterparts. For example, the hydraulic conductivity of rhyolitic lava flows on the east side of the impoundment area was estimated at 0.0001 feet/day, whereas interpretation of pumping tests of the unconsolidated alluvium near the center of Steptoe Valley estimated hydraulic conductivity of 400 feet/day (PTI 1994).

5.1.2.3 Description of Aquifers

The Paleozoic rocks and the alluvial fill in the valleys form the primary aquifers in the region; their hydraulic conductivities range from 0.1 to 400 feet/day. Groundwater in the Paleozoic aquifer can be confined or unconfined, and flow is controlled primarily by the occurrence of faults and fractures, secondary mineralization and alteration, and Tertiary intrusions. Groundwater in the alluvial aquifer is unconfined or, less commonly, semiconfined. Flow is controlled by elevation of the water table above mean sea level (MSL) and hydraulic conductivity contrasts within the alluvial sediments. The thickness of alluvium in White River Valley is greater than 1,050 feet near the impoundment. Monitoring well WCC-G1 was drilled to 1,050 feet near the center of the valley drainage, 1,500 feet south of the impoundment embankment, and the well encountered unconsolidated alluvial material to total depth.

5.1.2.4 Interaction Between Surface Water and Groundwater

There are no recognized perennial streams within the model domain. There are ephemeral streams that carry water from the mountain ranges forming the boundary of the valley floor. Giroux Wash, Jakes Wash, and several unnamed drainages at the head of White River Valley are ephemeral, containing surface water during the spring runoff and during storm events.

No naturally occurring surface-water bodies—including lakes, ponds, or springs—occur within the study area.

5.1.2.5 Aquifer Stresses

Precipitation in White Pine County is dependent on elevation; it ranges from approximately 6 inches/year in the valleys to >20 inches/year on the high peaks (Eakin et al. 1967). Recharge to groundwater (precipitation minus losses to evapotranspiration, runoff, and storage) is also dependent on elevation; the overall percentage of precipitation that reaches groundwater can vary from almost zero along the valley floors to as high as 25% in the mountainous areas (Maxey and Eakin 1949).

Snowmelt recharges the Paleozoic aquifers directly, and surface flow down mountain streams reaches the alluvial valleys and descends into the coarse alluvium along the mountain fronts to recharge the alluvial aquifers. Paleozoic aquifers may be directly recharged by alluvial basin-fill aquifers at depth. Rainfall also contributes to recharge in both aquifer systems.

Evapotranspiration from the groundwater table is most important in the valley floors where the water table is close to the surface. The depth at which evapotranspiration ceases is approximately 20 feet (Frick 1985; Leeds Hill 1981a). Evaporative losses are substantial from the pit lakes in the Robinson District; the pan evaporation rate is 48 inches/year (Houghton et al. 1975).

5.1.2.6 Boundary Conditions

No-flow boundaries were proposed for the east and west sides of the study area where the Egan, Butte, and White Pine Ranges form groundwater divides around the White River Valley. However, the eastern boundary of the model domain was not positioned at the Egan Range groundwater divide, and thus there was flow entering the system along this boundary. A constant head was assumed for the northern and parts of the southern boundaries to influence flow toward the south. These boundary conditions were appropriate for the area and were required to solve this mathematical problem using a numerical finite-difference method.

5.2 Mathematical Model

The groundwater flow model was implemented for the Giroux Wash site by using the numerical, three-dimensional code MODFLOW. The code uses a block-centered finite-difference model approach to solve the governing groundwater flow equation, which can be expressed as follows (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t}, \quad (5-1)$$

where

K_{xx} , K_{yy} , and K_{zz} are the values of hydraulic conductivity along the x , y , and z coordinate axes (LT^{-1});

h is the hydraulic head (L);

W is volumetric flux per unit volume and represents sources and/or sinks of groundwater (T^{-1});

S_s is the specific storage (L^{-1}); and

t is time (T).

To obtain a solution, the model domain was discretized into a finite-difference grid (see Section 4.5), and appropriate boundary conditions and representative hydrogeologic parameters were assigned to each grid node. MODFLOW then solved equation 5-1 for hydraulic heads and volumetric fluxes.

Development of a numerical groundwater flow model required the use of assumptions and approximations that simplify the physical system. Principal simplifying assumptions implicit in the implementation of MODFLOW include the following:

- groundwater flow is laminar;
- groundwater is isothermal, slightly compressible, and has uniform density;
- hydraulic conductivity is isotropic in the horizontal direction;
- the subsurface can be represented by a grid of cells and hydrogeologic parameters are constant within each cell;
- the physical parameters of the system do not change with the state of the system; and
- groundwater flow between model layers is vertical.

Review of site-specific data and consideration of model objectives indicated that these assumptions are acceptable and do not limit the applicability of the model for Giroux Wash.

A link was made between MODFLOW and HYDRUS_2D for inputting groundwater flux through the vadose zone to the water table. This structure provided a relatively seamless transition between the unsaturated and saturated flow models. Infiltrated water velocities predicted by HYDRUS_2D were incorporated into MODFLOW as recharge to the model layer at the water table.

5.3 Model Design

(1994)
A regional groundwater flow model developed by PTI, Inc., in support of the Environmental Impact Statement of the Robinson Project was used as the basis for the modeling investigation. The PTI model was refined and modified by incorporating more detailed hydrogeologic data to obtain finer hydraulic detail and resolution of flow vectors in the area of the tailings impoundment. A three-dimensional finite-difference numerical model was employed on a uniform, fine-grid mesh to solve the groundwater flow equation as applied to this study.

5.3.1 Model Domain

A finite-difference model grid mesh oriented north-south and aligned in the principal direction of groundwater flow and contaminant transport was developed (Figure 5-4). The rectangular model domain is 40,600 feet along the north-south dimension by 30,000 feet in the east-west dimension. It covered an area of about 44 square miles (1.218×10^9 square feet). There were nine layers within the model domain that ranged in thickness from 200 to 750 feet.

Model layers were assigned independently of geologic bedding and structure. Figure 5-5 shows the vertical discretization and how the bottom elevations of the nine model layers were held constant. The top elevation for the model, assigned on the basis of a digital topographic map, crossed model layers. Layers 5, 6, and 7 were the most important for

resolving the groundwater flow and contaminant transport at the Giroux Wash impoundment. First groundwater is encountered within these layers in the area of interest where contaminant transport to the south may occur.

5.3.2 Model Boundaries

Figure 5-6 displays the boundary conditions set in model layer 6. A no-flow boundary was assigned to the western boundary of the model domain, where the White Pine and Butte Ranges form a surface and groundwater divide. Constant heads were set on the northern and eastern boundaries where groundwater flow enters the model domain. A combination of constant head and no-flow boundaries was assigned to the southern boundary where groundwater exits the modeled system. Constant head values were estimated from water-level measurements of monitoring wells in the Giroux Wash area taken during the first quarter of 1997 and from regional head maps prepared by the USGS.

5.3.3 Hydraulic Properties

Hydraulic properties were estimated from tests performed on similar strata in other areas because no aquifer test data were available for the Giroux Wash area. Literature values were also used to verify the analogue aquifer test results.

5.3.3.1 Hydraulic Conductivity

Rock types described in the study area were incorporated into the groundwater flow model by assigning representative hydraulic conductivities to each. Stratigraphic variations were incorporated into the numerical model by varying hydraulic conductivity within each layer. This approach was similar to that taken to develop the previous regional groundwater model (PTI 1994).

Hydraulic conductivity values were estimated from previous investigations at the site including Dames & Moore (1982), PTI (1994), and HSI Geotrans (1996). Table 5-1 presents a summary of hydraulic conductivity values used for the individual rock types assigned during discretization of the numerical model and justifications for their use. Quaternary alluvial aquifers, composed of coarser-grained material, typically exhibit conductivities that range from 0.1 to 400 feet/day increasing from the valley edge to center. Conductivity of paleozoic limestone aquifers within the Giroux Wash area typically range from 1 to 20 feet/day. Tertiary volcanic rocks and fine-grained alluvial deposits have hydraulic conductivities that range from 0.0001 to 1 foot/day. Hydraulic conductivity was assigned to specific flow units based on stratigraphic or diagenetic properties (fracturing, mineralization, and dissolution) of that specific rock type. A range of hydraulic conductivity was assigned to rock types identified in the Giroux Wash area. For example, Quaternary alluvial sediments were allowed to vary from 0.01 to 400 feet/day over the model domain. Figure 5-7 displays the range of hydraulic conductivity values assigned to model layer 6. A similar plot, Figure 5-8, shows the variability of hydraulic conductivity over the model space for layer 7.

5.3.3.2 Specific Storage and Specific Yield

Previous aquifer testing performed by Dames & Moore (1982) and HSI Geotrans (1996) determined that storage coefficients ranged from 4×10^{-3} to 1×10^{-5} for confined and semiconfined flow units. Storage coefficients for alluvium at the Nevada Test Site ranging from 2×10^{-3} to 1×10^{-4} are in good agreement with these values. Specific yield for the unconfined aquifers was estimated at 0.05 to 0.23 from pumping tests in the adjacent areas. Table 5-2 summarizes storage terms used in the modeling study. Published literature data by McWhorter and Sunada (1977), Freeze and Cherry (1979), and Domenico and Schwartz (1990) confirms the storage terms used for the specific rock types encountered within the model domain.

fall within reasonable bounds

5.3.3.3 Porosity

Table 5-2 also summarizes porosity values assigned to the rock types encountered at Giroux Wash. An effective porosity of 0.25 was used for alluvial strata based on previous investigations completed at the site (PTI 1994). An effective porosity of 0.05 was assigned to the volcanic rocks. Estimated total porosity was converted to effective porosity according to the method of de Marsily (1986).

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9*

5.3.4 Aquifer Stresses

There are no active pumping wells located within the groundwater model domain. Also, mine dewatering activities north of the study area will have no impact on the impoundment area because they are on the far side of a groundwater divide formed by the Egan and Butte Ranges. Recharge and evapotranspiration are the only stresses acting on the local groundwater regime.

5.3.4.1 Recharge Calculations

Higher elevations receive more rainfall and allow a greater amount of deep percolation to the aquifers. Only a part of the precipitation will infiltrate through the unsaturated zone and recharge the groundwater system because a large percentage of the precipitation will be lost to evapotranspiration and surface runoff. Maxey and Eakin (1949) developed a water budget for White Pine County, which indicated that the fraction of precipitation recharging the aquifer is dependent on elevation, with an increasing fraction reaching the groundwater at higher elevations.

Therefore, the previous investigation (PTI 1994) calculated recharge by incorporating rainfall amounts predicted according to surface elevation. PTI developed a plot of precipitation vs. elevation based on average annual precipitation measured in gauges in the region. The plot of recharge shows that the highest recharge rates are estimated for the Egan Range area and recharge in the valley floor is lowest (Figure 5-9).

To incorporate the recharge into the groundwater model, the estimated recharge, R (in inches/year), as a function of elevation, E , was fit to the following equation with a correlation coefficient of $r = 0.95$ (coefficient of determination = $r^2 = 0.90$):

$$R = 0.534 \times \exp\left(\frac{0.28E}{1000}\right) - 3.029.$$

For every model cell, this equation provided an initial estimate for recharge that was based on the elevation of the center of the cell as determined from the topographic map. Recharge was assigned to the highest active model layer.

5.3.4.2 *Evaporation and Evapotranspiration Calculations*

In areas where the water table is closer to the land surface—which in the model domain primarily occurs in White River Valley south of the Giroux Wash impoundment—evaporation and transpiration by plants can occur from the water table surface. In fact, evapotranspiration in the lower elevations of Steptoe and White River Valleys generally exceeds precipitation, resulting in a net loss of groundwater from these areas of the basins (Maxey and Eakin 1949).

Therefore, an evapotranspiration curve was developed by assuming a maximum evapotranspiration rate of 48 inches/year for water at the land surface. This value is reasonably consistent with a maximum rate of 41 to 46 inches/year for evapotranspiration from the water table. The extinction depth for evapotranspiration was 20 feet (Frick 1985), and the rate was assumed to decrease linearly with depth.

More recent investigations have determined that there is a complex relationship between pan-evaporation rates and climatic conditions. However, the Giroux Wash area lies in a region of Nevada in which monthly and yearly average evapotranspiration rates fall in the lower end of the range for the state (Shevenell 1996) and thus are not significant contributions to aquifer stresses.

5.4 *Calibration*

A numerical calibration was performed for the steady-state groundwater flow model to prove that it was reasonably accurate and precise for its intended use of reproducing heads observed in the field. A primary objective of the calibration was to minimize the error of the numerical solution. Calibration of a flow model is a demonstration that the model is capable of reproducing the field-measured heads and fluxes that are the calibration values. The calibration was accomplished by determining the set of parameters, boundary conditions, and aquifer stresses that produced simulated heads that matched observed values, distributed spatially within the aquifer, within an acceptable range of error. This is the method prescribed by many authors including Anderson and Woessner (1992). Hydraulic conductivity was used as the calibration parameter to solve the inverse problem of developing the correct data set to accurately simulate measured heads. A qualitative calibration target set prior to modeling was ± 100 feet for all observation points evaluated.

5.4.1 Observation Points

The groundwater flow model was calibrated to seven monitoring wells situated around the periphery of the Giroux Wash impoundment. These wells were installed by Woodward Clyde Consultants in 1991 and by BHP in 1996. Monitoring wells were completed vertically over a range of several hundred feet. Five of the calibration targets (WCC-G2, WCC-G3, MW-G5, MW-G6, and PZ-G7) were completed in the equivalent of model layer 6, and two of the targets (WCC-G1 and PZ-G8) were completed in the equivalent of model layer 7. WCC-G4 was not included in the calibration because it is located in the region of faulting and volcanic intrusive rocks where it is very difficult to predict the rapid change in heads that occur across it.

5.4.2 Results of Steady-State Calibration

Results of the steady-state calibration statistics are included in Table 5-3. The groundwater sampling event of the first quarter of 1997 was used as the observed comparison for calibration purposes. The results indicate that the groundwater flow model is accurate at reproducing field-observed head values in multiple layers. An industry-standard suite of statistical analyses was performed for these data. The residual mean (RM) is defined as

$$RM = \frac{1}{n} \sum_i^n (h_o - h_s)_i, \quad (5-2)$$

Subsample

where

n = the number of observations or calibration points,

h_s = simulated head, and

h_o = observed head.

The residual mean is 2.7 feet for the target points available for calibration.

Absolute residual mean (ARM) is the absolute value of the residual mean, or

$$ARM = \frac{1}{n} \sum_i^n | (h_o - h_s)_i |, \quad (5-3)$$

The absolute residual mean is 36.9 feet for the seven calibration points.

The standard deviation (SD) of the simulated heads at the observation points is determined by

$$SD = \left[\frac{1}{n} \sum_i^n (h_o - h_s)^2 \right]^{0.5}, \quad (5-4)$$

RMS

The standard deviation for the model calibration targets was 53.2 feet. Range in heads (HR) for the observation points was 826 feet. A very useful measure of calibration results is to calculate the SD per HR of the observation points. This ratio gives a sense for the accuracy of the model over the calibrated area. Results of the steady-state calibration gave 0.06 (6%). According to Anderson and Woessner (1992), a calibrated flow model should have an SD/HR value of $>15\%$. ✓

This model appears to be accurate for predicting heads and flows over the area of interest as determined by the generally accepted protocol for quantitative evaluation of groundwater flow models.

Although there were just seven points with which to quantify the model, there were regional data from which to interpret groundwater flow away from the monitoring wells. As described in Section 3.1, groundwater flow originates in the ranges forming flow boundaries on roughly three sides of the model domain, and it flows southward toward the axis of the White River Valley. A qualitative evaluation of model-predicted heads for layer 6 reproduced the overall shape and corresponded closely with the interpreted water table map (Figure 5-11).

5.5 Verification and Sensitivity Analysis

Mass-balance error for the flow model was 0.9%, an acceptable mass-balance error according to Anderson and Woessner (1992).

Model sensitivity analysis, using industry-accepted protocol, was accomplished by adjusting the hydraulic parameters and evaluating the results. Final sensitivity to variation in hydraulic conductivity, vertical conductivity, recharge, and evapotranspiration is displayed on Table 5-4. The model was most sensitive to changes in recharge.

An analysis was performed to determine how sensitive the model is to uncertainty in various model input parameters. The relative sensitivity of the model to changes in input parameters was an indicator of the degree of importance of individual parameters to the simulation results.

The parameter groups varied during the sensitivity analysis were

- horizontal and vertical hydraulic conductivities,
- recharge, and
- evapotranspiration.

The parameter groups were varied by multipliers of 1.5 and 0.5 (i.e., $\pm 50\%$), for a total of eight simulations. Results of the sensitivity analysis were compared against the calibrated (base case) model. The results (Table 5-4) show that the model is most sensitive to changes in recharge, with horizontal conductivity being the second most sensitive

parameter. The model is least sensitive to changes in evapotranspiration and vertical hydraulic conductivity. Even though the increased lateral hydraulic conductivity case indicates improved statistics compared to the calibrated model, increasing the hydraulic conductivity was not justified, owing to the previous aquifer testing adjacent to the site. In addition, the result of the calibrated model and the increased lateral hydraulic conductivity case were statistically essentially identical.

5.6 Predictive Simulations

A total of 40 simulations, each with a 5,000-day stress period, was performed by using the calibrated groundwater flow model. Output from the HYDRUS_2D simulation of predicted infiltration velocity was input to the flow model as recharge. Meteoric recharge over the surface of the tailings impoundment was included in the unsaturated zone modeling described in Section 4. Simulations employing the predisposal conditions were assumed after this 200,000-day series of increased recharge by flushing through the vadose zone.

Steady-state simulations were selected for each of these stress periods because of the minor seasonal variations to aquifer stresses within the study area. These variations have been documented by measuring the hydraulic heads in the Giroux Wash monitoring wells over extended periods, as shown in the hydrographs for the WCC monitoring wells adjacent to the impoundment (Figure 5-12). It is apparent from Figure 5-12 that water levels in these wells have been essentially constant since their first sampling event.

An evaluation of the effect of increased recharge was modeled in steady and transient modes to determine what impact the increased infiltration estimated by HYDRUS_2D through the vadose zone would have on groundwater flow in the area. It was determined from the modeling results, comparing the 5000-day transient case against steady-state, that the system reaches equilibrium or pseudo steady-state within 500 days of the increased recharge stress. Figure 5-13 is a plot of head vs. time for WCC-G1 that displays the onset of steady-state conditions.

5.7 Interpretation of Modeling Results

Only minor changes in head and flux are realized by the aquifers in the region as a result of disposal of flotation tailings in the impoundment. Recharge increases during infiltration of the disposed water over the facility, but 100 years after initial disposal, recharge is predicted to have little impact on the groundwater flow and heads in model layer 6 (Figures 5-14). This observation modeling result is confirmed by comparing the layer-6 predisposal head distribution (Figure 5-11) to the layer-6 head distribution 100 years after disposal began (Figure 5-14).

5.8 Model Limitations and Assumptions

There are no aquifer tests of the saturated zone in the Giroux Wash area on which to base estimates of hydraulic parameters for input to the numerical model. Hydraulic conductivity—the calibration parameter—was assigned on the basis of analogue rock types in adjacent areas collected during previous investigations. For example, estimated hydraulic conductivity values determined from pumping tests performed on alluvial sediments in Steptoe Valley were applied to the Giroux Wash area. The steady-state flow model is calibrated over the region in which there are observation wells to act as calibration targets. There are a limited number of calibration targets on which to base the model accuracy and precision. Fortunately, all of the observation wells available for calibration were in the area of the impoundment in which the predicted concentrations and groundwater velocities to be resolved were critical for interpretation of future impacts to the POC well. Therefore, the numerical model is accurate for predicting groundwater flow and heads in the area near the impoundment.

6. Transport Modeling

The MT3D96 solute transport model was employed to predict aqueous-phase concentrations of sulfate downgradient of the Giroux Wash Tailings Impoundment. This solute transport code was linked to MODFLOW results to incorporate groundwater flows and heads, and it was linked to HYDRUS_2D to incorporate the sulfate concentrations infiltrated downward to the water table. Flow modeling results for the unsaturated and saturated zones that were input to the transport model assumed that climate-controlled parameters such as recharge and evapotranspiration did not change over the life of the simulations. Therefore, these flow modeling results assume no changes to weather patterns over this region of Nevada for thousands of years.

6.1 Conceptual Transport Model

Figure 4-2 depicts the conceptual migration of solute from the floor of the tailings impoundment through the vadose zone and to groundwater ~~aquifers~~ ^{aquifers}. Surface water disposed of in the impoundment will infiltrate the vadose zone and then migrate vertically to the water table.

6.2 Mathematical Model

Transport of COCs at the site was modeled by using the numerical, fully three-dimensional code MT3D. The code solved the advection-dispersion equation (e.g., Zheng 1992):

$$R \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (v_i C) + \frac{q_s}{\theta} C_{ss} - \lambda \left(C + \frac{\rho_b}{\theta} C_s \right), \quad (6-1)$$

where

R is the retardation factor (dimensionless);

C is chemical concentration in groundwater (ML^{-3});

t is time (T);

x_i values are the Cartesian coordinate axes (L);

D_{ij} is the hydrodynamic dispersion tensor (L^2T^{-1});

v_i values are the components of average linear groundwater velocity (LT^{-1});

q_s is the volumetric flux of water per unit volume of aquifer representing sources and sinks (T^{-1});

θ is porosity (dimensionless);

C_{ss} is the concentration of sources or sinks (ML^{-3});

λ is the first-order degradation-rate constant (T^{-1});

ρ_b is bulk density (ML^{-3}); and

C_s is chemical concentration sorbed to the porous medium (MM^{-1}).

The hydrodynamic dispersion tensor was defined by previous authors (e.g., Zheng 1992).

$$D_{xx} = \alpha_L \frac{v_x^2}{|v|} + \alpha_{TH} \frac{v_y^2}{|v|} + \alpha_{TV} \frac{v_z^2}{|v|} + D^*, \quad (6-2)$$

$$D_{xy} = D_{yx} = (\alpha_L - \alpha_{TH}) \frac{v_x v_y}{|v|}, \quad (6-3)$$

where

α_L is the longitudinal dispersivity (L);

α_{TH} is the horizontal transverse dispersivity (L);

D^* is the effective molecular diffusion coefficient (L^2T^{-1}); and

$|v|$ is the magnitude of the velocity vector (LT^{-1}).

There is also the third-dimensional component of this tensor that is not included here since it is similar to the horizontal component.

The retardation factor is defined as (Freeze and Cherry 1979)

$$R = 1 + \frac{\rho_b}{\phi} K_d, \quad (6-4)$$

where

K_d is the partition coefficient (L^3M^{-1});

ρ_b is the bulk density (ML^{-3}); and

ϕ is porosity (dimensionless).

MT3D solved equation 6-3 by a mixed Eulerian-Lagrangian method. The advection term was solved with the Lagrangian method by using one of three particle-tracking implementations:

- the forward-tracking method of characteristics (MOC),
- the backward-tracking modified method of characteristics (MMOC), or
- a hybrid of these two methods (HMOC).

The dispersion and chemical reaction terms were solved through a conventional explicit Eulerian block-centered finite-difference implementation.

Implementation of a numerical contaminant transport model requires the use of assumptions and approximations that simplify the physical system. The principal simplifying assumptions used in this transport model include the following:

- sorption follows a reversible linear isotherm and
- degradation follows a first-order rate-reaction law.

Just allowed to decay in this specific problem

6.3 Model Design Parameters

The average linear groundwater velocities were obtained from the MODFLOW groundwater-flow model, and they were used as input to the MT3D96 transport model.

6.3.1 Solute Fluxes

Background concentrations for sulfate and TDS were incorporated as 29 mg/L and 360 mg/L, respectively. A contaminant source was input into MT3D96 as temporal and spatially variable sulfate concentrations. The TDS concentration is assumed to be proportional to the sulfate concentration (Section 1.3). These concentrations were predicted by HYDRUS_2D as contaminant flux through the vadose zone to the water table. Sulfate concentration flux to the groundwater system was predicted over the lateral extent of the Giroux Wash impoundment. Concentrations are predicted for beneath the impoundment during the life of the anticipated transport through the unsaturated zone (forty 5000-day stress periods). Following the 200,000 day period of sulfate transport through the unsaturated zone, all water recharging the model was assumed to be at the background groundwater concentration of 29 mg/L of sulfate.

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where? at surface or water table

6.3.2 Dispersivity

The estimated longitudinal dispersivity (α_L) length of 450 feet was based on the scale of the problem evaluated. An average distance from the lower center part of the impoundment, where the centroid of the plume is anticipated, to the WCC-G1 POC well is 4,500 feet. Dispersivity equal to 10% of the distance the plume will travel is a reasonable estimate (Domenico and Schwartz 1990), and the value of 450 feet was derived from this. The ratios of transverse dispersivity (α_T) to α_L of 0.33 and of vertical dispersivity (α_V) to α_L of 0.0533 were used from previous studies (PTI 1994).

6.3.3 Molecular Diffusion

Molecular diffusion was estimated at 1×10^{-5} cm²/s for the entire model domain. This value was chosen during previous site investigations (PTI 1994).

6.3.4 Chemical Reactions

No chemical reactions, including sorption or biodegradation, were assigned or simulated in the groundwater transport model. Conservative transport was assumed. Only hydrodynamic dispersion and dilution via groundwater flux through the system were responsible for attenuating sulfate concentrations.

6.4 Predictive Transient Simulations

A series of forty 5000-day stress periods (548 years, as required for the complete flushing of the vadose zone predicted by HYDRUS_2D [Section 4.8]) was run using MT3D96 to simulate sulfate transport from the tailings impoundment area during disposal and postdisposal of processed water. During this period, all solutes from the tailings impoundment percolated to groundwater finishing with background solute concentrations throughout the vadose zone. Beyond these 40 stress periods, the transport model was then run for an additional 1,096 years at predisposal conditions, assuming steady flow, to estimate maximum sulfate concentration at the POC well WCC-G1. Groundwater flow and heads from MODFLOW were input into the transport model, and sulfate flux to the groundwater as predicted by HYDRUS_2D was also incorporated into the model.

The suite of transport solvers was evaluated via a simple test case, and it was determined that the hybrid method of characteristics (HMOC) particle-tracking solver was appropriate for solving this field problem. HMOC gave the best combination of accuracy and processing speed. The HMOC solver uses the method of characteristics (MOC) particle-tracking algorithm in areas with sharp concentration fronts and the modified method of characteristics (MMOC) in areas without sharp concentration fronts. This solver minimizes numerical dispersion while optimizing the processing speed of the problem. Processing speed was important because the modeling was simulating multiple-layer three-dimensional transport for more than 1600 years. Numerical oscillations appeared in the upstream finite-difference model solver, and because of these instabilities, it was not deployed. The pure MMOC solver was not employed because of the potential problems with nonuniform flow fields and the possibility for advection-dominated transport. MOC required the most time to complete the test case simulation and was therefore not used.

6.5 Interpretation of Modeling Results

6.5.1 Case 1—3,000 mg/L TDS Source

Simulated sulfate concentrations reach a maximum of approximately 41 mg/L, 750 years in the future at the POC well, WCC-G1 (Figure 6-1). This value is an increase of only 12 mg/L above the naturally occurring groundwater sulfate concentrations. Sulfate concentrations are predicted to plateau for several hundred years and then gradually decrease at the POC well after 1200 years. The modeled sulfate concentrations remained above the background concentrations for the remainder of the simulation, but steadily decreased.

East side of wash?

A breakthrough curve for TDS at the POC well, assuming a 3000 mg/L source concentration, is shown in Figure 6-2. Predicted TDS concentrations can be scaled to the modeled sulfate concentrations because there is a linear relationship between sulfate and TDS concentrations in the infiltrating water. By adjusting the predicted increases in sulfate concentrations by the ratio of TDS to sulfate concentration for a 3000 mg/L concentration source in the impoundment, the resulting increases in TDS concentrations at the POC well ~~can be~~ calculated. At 750 years in the future, the TDS concentrations at the POC well reach a maximum of 377 mg/L.

were

It can be interpreted from these breakthrough curves (Figures 6-1 and 6-2) that sulfate and TDS will not exceed 41 and 377 mg/L, respectively. These values are below the State of Nevada Drinking Water Standards. The highest concentrations of these two constituents at the POC well will not be realized until approximately 750 years after disposal was initiated.

Isoconcentration maps constructed at 96 years in the future show that sulfate reaches highest concentrations in layer 5, with a maximum simulated value of 204 mg/L (Figure 6-3). Lower concentrations are predicted in layer 6 and 7, in which the maximum levels simulated at 96 years are 64 mg/L and 41 mg/L respectively (Figures 6-4 and 6-5). Maximum solute flux to the water table is predicted approximately 96 years from the present. The modeled concentrations 548 years in the future are displayed for layers 6 and 7 in Figures 6-6 and 6-7, respectively. Maximum sulfate concentrations after 548 years are predicted as 90 mg/L in layer 6 and 62 mg/L in layer 7 beneath the impoundment structure. The total mass of disposed water will be flushed through the vadose zone by 548 years after disposal operations cease.

Sulfate concentrations for layers 6 and 7 after 1,644 years of transport are shown in Figures 6-8 and 6-9, respectively. The maximum concentrations are 49 mg/L and 55 mg/L for layers 6 and 7, respectively. This transport time is after the predicted sulfate concentrations at the POC have begun to gradually decrease.

6.5.2 Case 2—4,000 mg/L TDS Source

A breakthrough curve for TDS and sulfate constituents, assuming a 4,000 mg/L source, at the POC well is included (Figure 6-10). Predicted TDS concentrations can be scaled to the modeled sulfate concentrations because there is a linear relationship between sulfate and TDS concentrations in the infiltrating recharge water. By adjusting the predicted increases in sulfate concentrations by the ratio of TDS to sulfate concentration for a 4,000 mg/L concentration source in the impoundment, the resulting TDS concentrations at the POC well peak at slightly less than 382 mg/L.

Maximum sulfate concentrations will occur at the same time as in case 1, but are estimated to be approximately 44 mg/L. This estimate was obtained by taking the ratio of sulfate concentration at the source for case 2 to that for case 1 (2,760 mg/L : 2,100 mg/L) and multiplying modeled increases in sulfate concentrations by that value.

6.5.3 Case 3—5,000 mg/L TDS Source

A breakthrough curve for TDS and sulfate constituents, assuming a 5,000 mg/L source, at the POC well is included (Figure 6-11). The same relationships as described above were incorporated to predict TDS concentrations for a 5,000 mg/L source. By adjusting these predicted values for a 5,000 mg/L concentration source in the impoundment, the resulting TDS concentrations in the POC well in layer 7 reach maximum concentration of 387 mg/L.

Maximum sulfate concentration will occur at the same time as in case 1, but is estimated to be approximately 48 mg/L. This estimate was obtained by taking the ratio of sulfate concentration at the source for case 3 to that for case 1 (3,450 mg/L : 2,100 mg/L) and multiplying modeled sulfate concentrations by that value.

6.6 Model Limitations and Assumptions

These simulations assume that there are no major climatological changes in this area of Nevada over the entire simulation length. The simulations were conducted for almost 2,000 years, given the rate of groundwater flow compared to the size of the model domain, making the lack of climatological change an important assumption.

The limited area for the transport model simulation owing to the interest focused on the POC well (WCC-G1) constrained the predictive results to the immediate vicinity of Giroux Wash. Predictions of the fate of the sulfate and TDS far downgradient of the WCC-G1 monitoring well were not completed during this investigation. There were no initial conditions to calibrate the solute transport model to. Having initial conditions would have enabled checking the assumed dispersivity and other solute transport parameters.

The resolution of the modeled sulfate concentrations reflect^s the model domain discretization. The vertical discretization results in an averaging of the solute concentrations through_W out the individual model cell thickness (200 feet × 200 feet).

The conservative assumptions of no attenuation of the TDS and sulfate built into the three groundwater solute transport cases represent a worst case scenario for the sulfate transport in the ground water.

7. Conclusions

Groundwater flow and solute transport modeling was completed for the Giroux Wash Tailings Impoundment pursuant to Section 2.9.2 of the February 27, 1997, *Work Plan—Robinson Operations*. Well-benchmarked U.S. Geological Survey and U.S. Environmental Protection Agency models were combined to quantify tailings solution percolation and solute transport through the vadose zone to groundwater, followed by saturated zone flow and solute transport to the downgradient compliance point (well WCC-G1).

The subregional Giroux Wash model assumed continued tailings solution deposition into the impoundment for the remaining mine life of 16 years. Postclosure conditions implemented in the model assumed that no cap or cover will be installed over the impoundment. The model evaluated three cases of tailings solution concentrations—3,000 mg/L, 4,000 mg/L, and 5,000 mg/L—to account for TDS variations in mill process water. The model accounted for future impoundment development through sequentially increased impoundment surface area and volume. The model implemented the following conservative flow and transport assumptions:

- Seepage will occur over the entire footprint of the impoundment for the operational life of the facility.
- The supernatant pond was assumed to provide an equivalent head across the lateral extent of the impoundment.
- No sorption or retarded transport of solutes will occur.
- The solutes will not be subject to any chemical reactions.
- Worst-case scenarios for source concentrations were modeled.
- Low-permeability soils (i.e., "B" horizon) were not incorporated in the vadose zone model.

These assumptions provided for maximum predicted flow velocities and advective solute transport. The model assumed that future climatic conditions in east-central Nevada would remain similar to current conditions over the modeled period of 1,644 years.

The purpose for conducting this modeling effort was twofold:

- to evaluate tailings solution percolation through the unsaturated zone below the impoundment and
- to assess the potential for degradation of state waters.

The model was successful in addressing these two objectives, as discussed below.

7.1 Tailings Solution Percolation Through the Unsaturated Zone

Unsaturated zone modeling predicted tailings solution percolation and solute transport through alluvium and volcanic rock composing the Giroux Wash subsurface. The travel time required for the initial wetting front to reach groundwater differs considerably across the Giroux Wash fault because of the differences in depth to groundwater.

West of the fault, a thick alluvial sequence underlies Giroux Wash, with groundwater residing approximately 750 feet below ground surface. Model results indicate that the initial wetting front will require 100 years to reach groundwater west of the fault, with percolation continuing 548 years thereafter until free water residing within the impoundment completely percolates through the vadose zone to groundwater.

East of the fault, relatively thin alluvium and volcanic rock compose the Giroux Wash subsurface, hosting groundwater at approximately 250 feet below ground surface. The initial wetting front will require 16 years to reach groundwater east of the fault, with tailings solution continuing to percolate for 100 years thereafter. M M M M

Conservative model assumptions (maximized relative solute concentrations and minimized travel time) within the bounds of the Giroux Wash characterization were implemented to quantify peak solute concentration discharging to groundwater via vertical tailings solution percolation. West of the Giroux Wash fault, peak conservative solute concentration reaching the water table is approximately 8% of the impounded tailings solution concentration, after approximately 356 years. East of the fault, peak solute concentration reaches approximately 33% of the impounded tailing water after approximately 36 years.

7.2 Potential for Groundwater Degradation

Saturated zone solute transport modeling predicted that peak conservative solute concentration will increase by 10 to 20 mg/L (owing to tailings solution migration) over the next 500 to 1,000 years at WCC-G1 and then gradually decrease back to baseline concentrations at 1,370 years in the future.

The model results predict a maximum TDS of 387 mg/L at well WCC-G1. The peak TDS concentration is predicted to occur within 500 years at the earliest, given an impounded tailings solution TDS concentration of 5,000 mg/L. Model results therefore indicate that vertical percolation of tailings solution from the impoundment to groundwater underlying Giroux Wash will not lead to an exceedance of NDEP water-quality standards for TDS of 1,000 mg/L.

Model results predict a maximum sulfate concentration of 48 mg/L at well WCC-G1 as early as 600 years in the future, given an impounded tailings solution sulfate concentration of 5,000 mg/L. These results support TDS modeling results discussed

above and indicate that sulfate concentrations will not exceed the NDEP water-quality standard of 500 mg/L at well WCC-G1.

In summary, conservative transport parameters assigned for transport modeling results indicate that subsurface discharge of percolating tailings solution will not lead to degradation of state waters, as solute concentrations do not exceed NDEP water-quality standards at the downgradient compliance point (monitoring well WCC-G1).

8. Recommendations

Groundwater flow and solute transport modeling for the Giroux Wash Tailings Impoundment predicts slow, vertical percolation of tailings solution through the Giroux Wash vadose zone to groundwater. Model results predict no substantial increase in conservative solute concentration in groundwater at the compliance monitoring point (WCC-G1). Consequently, model results indicate no degradation of state waters. The model results support continued operation of the tailings impoundment throughout the remaining mine life of approximately 16 years.

Results of the modeling effort, which incorporated conservative flow and transport assumptions, are germane to evaluating any potential benefits of lining the barge operating channel. Although tailings deposition will displace free water as the impoundment is filled, the model incorporated an initial 5-foot free hydraulic head (SRK, 1997) across the entire impoundment footprint, as a conservative starting condition. This starting hydraulic head is equivalent to the average head in the supernatant pond and barge operating channel, and thus the model assumes that the supernatant pond covers the entire impoundment. Model results indicate no degradation of state waters at the POC from tailings solution infiltration. Therefore, under current and future operating conditions, vertical tailings solution infiltration from the unlined barge operating channel (ultimately covering only a small fraction—0.1%—of the total impoundment footprint) will not lead to degradation of state waters.

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Tables

Table 1-1. Summary Tailings Data for Robinson District

pH, TDS, calcium, sulfate

Sample ID:	Date:	Parameters:			
		pH	TDS	Calcium	Sulfate
Repulp House	1/31/96	10.4	1790	520	1030
	2/28/96	10.7	2530	731	1450
	3/26/96	10.1	2470	689	1520
	7/11/96	10.38	2590	668	1600
	April	9.22	2150	573	1330
	5/14/96	9.49	2360	398	1370
	1/31/96	10.4	1790	520	1030
	2/28/96	10.7	2530	731	1450
	3/26/96	10.1	2470	689	1520
	4/15/96	9.22	2150	573	1330
	5/14/96	9.49	2360	598	1370
	6/12/96	9.84	1610	924	1610
	6/20/96	9.29	2620	761	1640
	6/27/96	10.48	2580	676	1430
	7/3/96	9.88	2710	723	1640
	7/25/96	5.33	2510	787	1650
	8/2/96	9.63	2500	699	1480
	8/16/96	8.79	2010	557	1160
	8/23/96	6.47	1640	407	904
	9/20/96	6.95	2680	653	1810
	10/31/96	6.9	1290	348	699
	11/15/96	8.62	1540	387	896
	12/2/96	9.28	1390	384	842
	12/19/96	8.65	1410	304	766
	12/31/96	9.8	1450	389	842
	10:00 3/16/97		1310		
	3:00 3/16/97		1880		
	10:00 3/17/97		1732		
	3:00 3/17/97		2152		
	5:30 3/18/97		1540		
	9:00 3/18/97		2280		
	10:00 3/19/97		1500		
	3:00 3/19/97		1364		
	10:00 3/20/97		1370		
	3:00 3/20/97		1464		
	10:00 3/21/97		1512		
	3:00 3/21/97		1444		
	10:00 3/22/97		496		
	3:00 3/22/97		1444		
	10:00 3/23/97		1732		
	3:00 3/23/97		1608		
	10:00 3/24/97		1576		
	3:00 3/24/97		1176		
	10:00 3/25/97		660		
	3:00 3/25/97		688		
	10:00 3/26/97		1180		
	3:00 3/26/97		1140		
	10:00 3/27/97		1420		
	15:00 3/27/97		1288		
	10:00 3/28/97		1256		
	15:00 3/28/97		1368		
	5/28/97		2256		
	"		1956		
	10:00 4/4/97		1512		
	3:00 "		1444		

Table 1-1. Summary Tailings Data for Robinson District
pH, TDS, calcium, sulfate

Sample ID:	Date:	Parameters:		Calcium	Sulfate
		pH	TDS		
	10:00 "		496		
	3:00 "		1444		
	10:00 "		1732		
	3:00 "		1608		
	10:00 4/4/97		1576		
	10:00 "		1176		
	3:00 "		660		
	10:00 "		688		
	10:00 "		1180		
	3:00 "		1140		
	10:00 4/4/97		1420		
	15:00 "		1288		
	10:00 "		1256		
	3:00 "		1368		
<hr/>					
Pump House	1/5/96	9.41	1260	283	782
	2/27/96	10.8	2070	599	1390
	3/26/96	8.82	2170	479	1240
	4/15/96	9.57	2110	564	1330
	5/14/96	7.01	1300	312	730
	6/12/96	8.5	2380	862	1500
	6/20/96	9.54	2590	605	1670
	6/27/96	11	2800	813	1520
	6/27/96	10.41	2580	817	1480
	7/3/96	9.6	2680	693	1620
	7/11/96	10.54	2540	677	1560
	7/25/96	6.5	2470	647	1560
	8/2/96	10.13	2600	566	1470
	8/2/96	10.12	2540	679	1480
	8/9/96	11.04	2550	807	1470
	8/16/96	9.11	1990	550	1130
	8/23/96	9.63	1650	405	840
<hr/>					
Reclaim	1/3/96	8.25	1720	382	1100
	1/8/96	8.64	1570	412	954
	2/27/96	10	2460	634	1400
<hr/>					
Mill Slurry	12/16/95	12.1	2310	1400	641
	12/18/95	8.26	1480	332	946
	12/30/95	8.68	1450	328	916
<hr/>					
Impoundment	3/28/96	10	2490	589	1520
	4/15/96	9.22	2150	573	1330
	7/11/96	10.3	2660	824	1510
	7/25/96	9.05	2490	804	1520
	1/13/97	7.51	3040	674	2100
<hr/>					
Thickener	6/20/96	9.1	2510	610	1570
	7/3/96	10.5	2660	683	1540
	7/11/96	10.94	2390	661	1390
<hr/>					
AVERAGE		9.31	1821.63	603.87	1308.30
ST. DEVIATION		1.29	597.69	195.85	325.28
Average TDS for Samples with Ca and SO4 data			2192.68		

min

max

Table 1-1. Summary Tailings Data for Robinson District

pH, TDS, calcium, sulfate

Sample ID: <i>Depth</i>	Date:	Parameters:			
		pH	TDS	Calcium	Sulfate
MW-4G	8/10/95	7.87	325	59.8	35.9
MW-4G	11/7/95	7.77	281	38.5	35.6
MW-4G	3/11/96	7.82	260	26.6	19
MW-4G	4/23/96	7.94	252	33.1	16
MW-5G	8/9/95	7.69	338	36.1	30.8
MW-5G	11/9/95	7.99	287	38.2	26.3
MW-5G	3/25/96	7.86	282	47.3	23
MW-5G	4/28/96	7.94	284	46.2	22
WCC-G1	5/17/93	7.89	634	107	34.5
WCC-G1	10/8/93	7.7	542	101	32.5
WCC-G1	3/29/94	7.63	606	103	33.9
WCC-G1	9/23/94	7.86	580	91	28.7
WCC-G1	4/5/95	8.11	552	92.5	26.3
WCC-G1	8/2/95	7.87	572	93.7	30.3
WCC-G1	9/22/95	7.94	551	92.4	28
WCC-G1	3/20/96	8.12	578	93	27
WCC-G1	4/23/96	8.05	528	77.9	25
WCC-G2	5/14/93	8.44	580 ?	44.4	40
WCC-G2	10/7/93	8.1	239	46.4	28.9
WCC-G2	3/28/94	8.26	246	43.2	28.8
WCC-G2	9/7/94	8.24	271	44.5	28.1
WCC-G2	4/5/95	8.22	260	44.9	27.5
WCC-G2	8/1/95	8.04	255	45.1	29
WCC-G2	9/22/95	8.07	250	45.5	27.8
WCC-G2	11/20/95	8.12	265	42.4	28.7
WCC-G2	3/22/96	8.29	266	43.1	30
WCC-G2	4/28/96	8.22	264	45.8	28
WCC-G3	3/28/94	8.25	269	41.8	32.7
WCC-G3	9/23/94	8.28	272	44.1	33.2
WCC-G3	4/5/95	8.98	395	75.5	41.7
WCC-G3	8/2/95	8.15	260	44	32.1
WCC-G3	9/22/95	7.67	489	85	30.5
WCC-G3	11/20/95	7.74	601 ?	127	25.6
WCC-G3	4/23/96	7.73	224	30.8	36
AVERAGE		8.03	378.18	60.91	29.51
STD. DEVIATION		0.27	144.64	26.83	5.25

Table 2-1. Stratigraphy, Lithology and Average Thickness of Geologic Units

Symbol	Lithologic Code	Thickness (ft) ^b	Age	Formation/Lithologic Description
Qal/Qoal	1	0-2,000+	Quaternary ^a	Alluvium/Older alluvium
T _{vb}	2	1,000+	Tertiary	Welded tuff (prophyritic rhyolite)
T _{sp}	3	1,000+	Tertiary	Sheep Pass Fm (conglomerate and limestone)
T _{vf}	2	na	Tertiary	Quartz rhyolite lava flows
T _{vt}	2	na	Tertiary	Unwelded tuff (rhyolite)
T _{va}	2	na	Tertiary	Ash and agglomerate
Pk	4	150-400	Permian	Kaibab Limestone
Pau/Pal	5	1,500-1,600 (Pau) 1,200-1,500 (Pal)	Permian	Arcturus Fm (siltstone interbedded with limestone)
Prh	3	1,100-1,200	Permian	Rib Hill sandstone (w/ interbedded limestone)
Prs	4	275-350	Permian	Riepe Spring Limestone of Steele
Pe	4	2,450-2,600	Permian	Ely Limestone (w/ interbedded sandstone)

^a Thickness of Steptoe valley alluvium up to 11,000 ft near McGill (Frick 1985).

^b Tabled information based on USGS geologic quadrangles for Ely area and Langenheim and Larson, 1973, and Welsh Engineering Inc., 1991.

Table 4-1. Hydraulic Parameters for the Unsaturated Zone Model

RECHARGE THROUGH SURFACE OF NATIVE SOILS		
Recharge Rate	Value	Reference
Operating Rate	7.6×10^{-3} ft/day	see Section 2.4.1
Post-Closure Rate	6.6×10^{-4} ft/day	Saturated Zone Model (Section 5)

ALLUVIAL HYDRAULIC PARAMETERS

Parameter	Units	Value	Reference
Saturated Hydraulic Conductivity	t/day	28.5	WESTEC, 1991
Porosity	cm ³ /cm ³	0.25	PTI, 1994
Residual Water Content	cm ³ /cm ³	0.07	PTI, 1994
van Genuchten α parameter	cm ⁻¹	0.02	Simunek, 1996
van Genuchten n parameter		1.41	Simunek, 1996

SANDSTONE HYDRAULIC PARAMETERS

Parameter	Units	Value	Reference
Saturated Hydraulic Conductivity	ft/day	0.014	PTI, 1994
Porosity	cm ³ /cm ³	0.08	PTI, 1994
Residual Water Content	cm ³ /cm ³	0.04	PTI, 1994
van Genuchten α parameter	cm ⁻¹	0.005	Simunek, 1996
van Genuchten n parameter		1.09	Simunek, 1996

LIMESTONE HYDRAULIC PARAMETERS

Parameter	Units	Value	Reference
Saturated Hydraulic Conductivity	ft/day	0.014	PTI, 1994
Porosity	cm ³ /cm ³	0.08	PTI, 1994
Residual Water Content	cm ³ /cm ³	0.04	PTI, 1994
van Genuchten α parameter	cm ⁻¹	0.005	Simunek, 1996
van Genuchten n parameter		1.09	Simunek, 1996

Table 4-2. Solute Transport Parameters

ALLUVIAL TRANSPORT PARAMETERS			
Parameter	Units	Value	Reference
Bulk Density	g/cm ³	1.6	WESTEC, 1991
Diffusion Coefficient	cm ² /day	20	Jury, 1991
Dispersion	cm ² /day	20	Jury, 1991
Partition Coefficient (Kd value)	L/Kg	0	conservative assumption (see Section 2.4.3)
Reactivity		none	conservative assumption (see Section 2.4.3)
SANDSTONE TRANSPORT PARAMETERS			
Parameter	Units	Value	Reference
Bulk Density	g/cm ³	2.2	WESTEC, 1991
Diffusion Coefficient	cm ² /day	10	Jury, 1991
Dispersion	cm ² /day	10	Jury, 1991
Partition Coefficient (Kd value)	L/Kg	0	conservative assumption (see Section 2.4.3)
Reactivity		none	conservative assumption (see Section 2.4.3)
LIMESTONE TRANSPORT PARAMETERS			
Parameter	Units	Value	Reference
Bulk Density	g/cm ³	2.3	WESTEC, 1991
Diffusion Coefficient	cm ² /day	10	Jury, 1991
Dispersion	cm ² /day	10	Jury, 1991
Partition Coefficient (Kd value)	L/Kg	0	conservative assumption (see Section 2.4.3)
Reactivity		none	conservative assumption (see Section 2.4.3)

Table 5-1. Model: Hydraulic Conductivities

Rock Type	Model Zone Number	Hydraulic Conductivity (ft/day)			Reference
		X1 X	X2 Y	X3 Z	
Conf Pz*	27	32.0	32.0	0.3	a
Conf Pz*	28	40.0	40.0	0.4	
Conf Pz*	29	80.0	80.0	0.8	
Conf Pz*	30	160.0	160.0	16.0	
Conf Pz*	31	320.0	320.0	3.2	
Conf Pz*	32	1600.0	1600.0	1.6	
Conf Pz*	33	3200.0	3200.0	320.0	
Conf Pz*	34	4000.0	4000.0	40.0	
Conf Pz*	35	8000.0	8000.0	80.0	
Conf Pz*	36	16000.0	16000.0	160.0	
Conf Pz*	37	32000.0	32000.0	320.0	b
Conf Pz*	38	50000.0	50000.0	50000.0	
Pau/Prh	51	0.05	0.05	5.0E-05	
Pz	2	0.001	0.001	0.001	
Pz	3	0.002	0.002	2.0E-04	
Pz	6	0.010	0.010	0.010	
Pz	7	0.020	0.020	0.020	
Pz	8	0.025	0.025	0.025	
Pz	9	0.1	0.1	0.0	
Pz	12	0.4	0.4	0.4	
Pz	13	0.8	0.8	0.8	c
Pz	14	1.0	1.0	1.0	
Pz	15	1.2	1.2	1.2	
Pz	16	1.6	1.6	0.016	
Pz	17	2.0	2.0	2.0	
Pz	18	2.3	2.3	2.3	
Pz	19	3.2	3.2	0.0	
Pz	21	5.0	5.0	5.0	
Pz	22	6.4	6.4	6.4	
Pz	23	8.0	8.0	8.0	
Pz	24	10.0	10.0	10.0	d
Pz	25	16.0	16.0	0.2	
Pz	26	20.0	20.0	2.0	
Pz	52	0.010	0.010	0.001	
Qa	10	0.1	0.1	0.01	
Qa	39	5.0	5.0	0.5	
Qa	45	0.010	0.010	0.001	
Qa	49	400.0	400.0	40	
Qa	55	1.0	1.0	0.1	
Qa	59	0.1	0.1	0.0	
Qa	60	0.001	0.001	1.0E-06	b
Tsp/Prh	11	0.2	0.2	0.0	
Tv	1	4.8E-04	4.8E-04	4.8E-04	
Tv	4	4.0E-03	4.0E-03	4.0E-04	
Tv	5	5.0E-03	5.0E-03	5.0E-04	
Tv	46	5.0E-02	5.0E-02	5.0E-06	

Key:

Conf Pz* - Confined Paleozoic Carbonate Rock, Transmissivity Used

Pau/Prh - Paleozoic Siltstones and Sandstones

Pz - Paleozoic Carbonate Rocks

Qa - Quaternary Alluvium

Tsp - Tertiary Sheep Pass Conglomerates

Tv - Tertiary Volcanic Rocks

References:

^a Dames & Moore 1982, 1988, 1990, Ely limestone near McGill: 1.1 - 15 ft/day

^b Westec, 1991, Giroux Wash: 0.00 - 0.6 ft/day

^c Dames & Moore, 1982, 1988, 1990, Steptoe Valley 0.005-3 ft/day; LeedsHill 1981, Steptoe Valley 5.7e+04 - 5.7e+5 ft/day; WESTEC 1991, Giroux Wash 0.02 - 0.6 ft/day

^d WESTEC 1991, Giroux Wash 1e-03 - 0.05 ft/day

Handwritten: 3 references

Table 5-2. Storage Properties Used in Model

Rock Type	S_s	S_y	Φ
Quaternary Alluvium	1×10^{-4} ^a	0.5 – 0.15	.25
Tertiary Volcanics	3×10^{-6} ^b	0.02 – 0.47	.08
	-7×10^{-5}		
Paleozoic Carbonates	2×10^{-5} ^a	—	.08
	-4×10^{-3}		

^a Dames and Moore, 1982, 1988, and 1990, Steptoe Valley

^b Morris and Johnson, 1962, Summary of Hydrological and Physical Properties of Rock and Soil Materials. USGS, Water Supply Paper, 1839-0.

Table 5-3 Groundwater Flow Model Calibration Statistics

Well	Observed heads(ft)	Simulated heads (ft)	Residual (ft)	Abs Res (ft)	Res squ (ft2)
mw-g6	5804.00	5802.13	1.87	1.87	3.50
mw-g5	5805.00	5795.18	9.82	9.82	96.43
wcc-g1	5814.90	5793.87	21.03	21.03	442.26
wcc-g3	6476.80	6386.20	90.60	90.6	8208.36
pz-g7	6597.50	6614.39	-16.89	16.89	285.27
pz-g8	6598.00	6700.75	-102.75	102.75	10557.56
wcc-g2	6630.10	6614.72	15.38	15.38	236.54

Observed Range in Heads: 826.10

Mean Error (ft)	Mean Abs Error (ft)	Standard Deviation (ft)	Std Dev/Range Hds
2.72	36.91	53.22	0.06

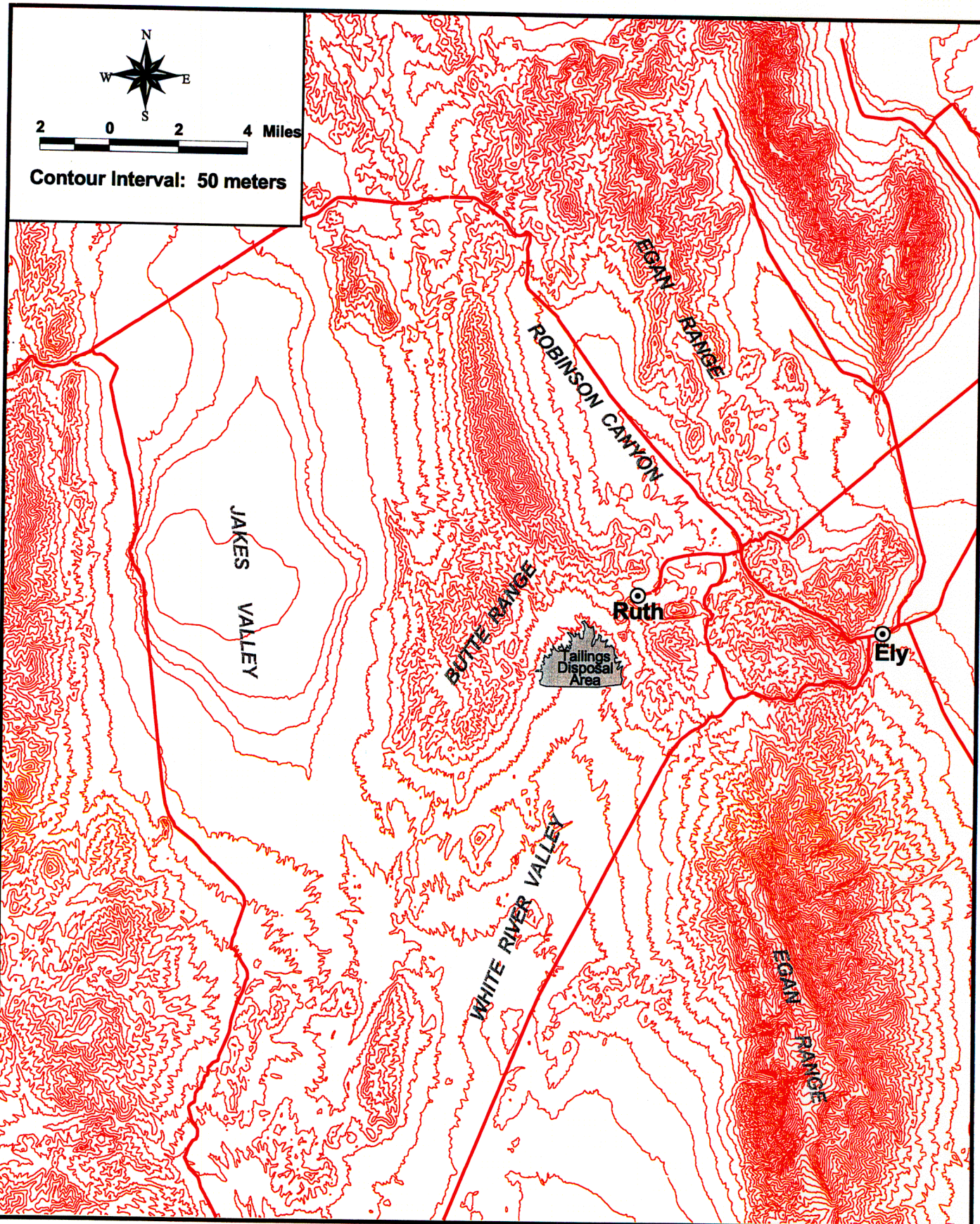
Table 5-4. Sensitivity Analysis

Simulation	Residual Mean	Standard Deviation	Ratio of Standard Deviation to Range in Head
Calibrated Model	2.70	53.20	0.064
Increase K_h by a Factor of 1.5	-0.07	47.26	0.057
Decrease K_h by a Factor of 0.5	0.11	64.75	0.078
Increase K_v by a Factor of 1.5	2.90	52.46	0.064
Decrease K_v by a Factor of 0.5	2.90	52.46	0.064
Increase Recharge by a Factor of 1.5	-4.97	56.73	0.069
Decrease Recharge by a factor of 0.5	10.94	49.08	0.059
Increase Evapotranspiration by a Factor of 1.5	2.90	52.46	0.064
Decrease Evapotranspiration by a Factor of 0.5	2.50	52.70	0.064

Table 6-1. Solute Transport Properties Used in Model

Parameter	Value	Reference
Longitudinal Dispersivity (α_L)	450 feet	10% of the Distance From POC to lower center of Impoundment
Transverse Dispersivity (α_T)	150 feet	Ratio of α_T to α_L Used by PTI (1994)
Vertical Dispersivity (α_V)	24 feet	Ratio of α_V to α_L Used by PTI (1994)
Porosity	0.25 or 0.8	See Table 5-1
Molecular Diffusion	1×10^{-5} cm ² /day	PTI (1994)
Partition Coefficient (Kd)	0	Conservative Transport Assumption
Decay Constant K	0	Conservative Transport Assumption

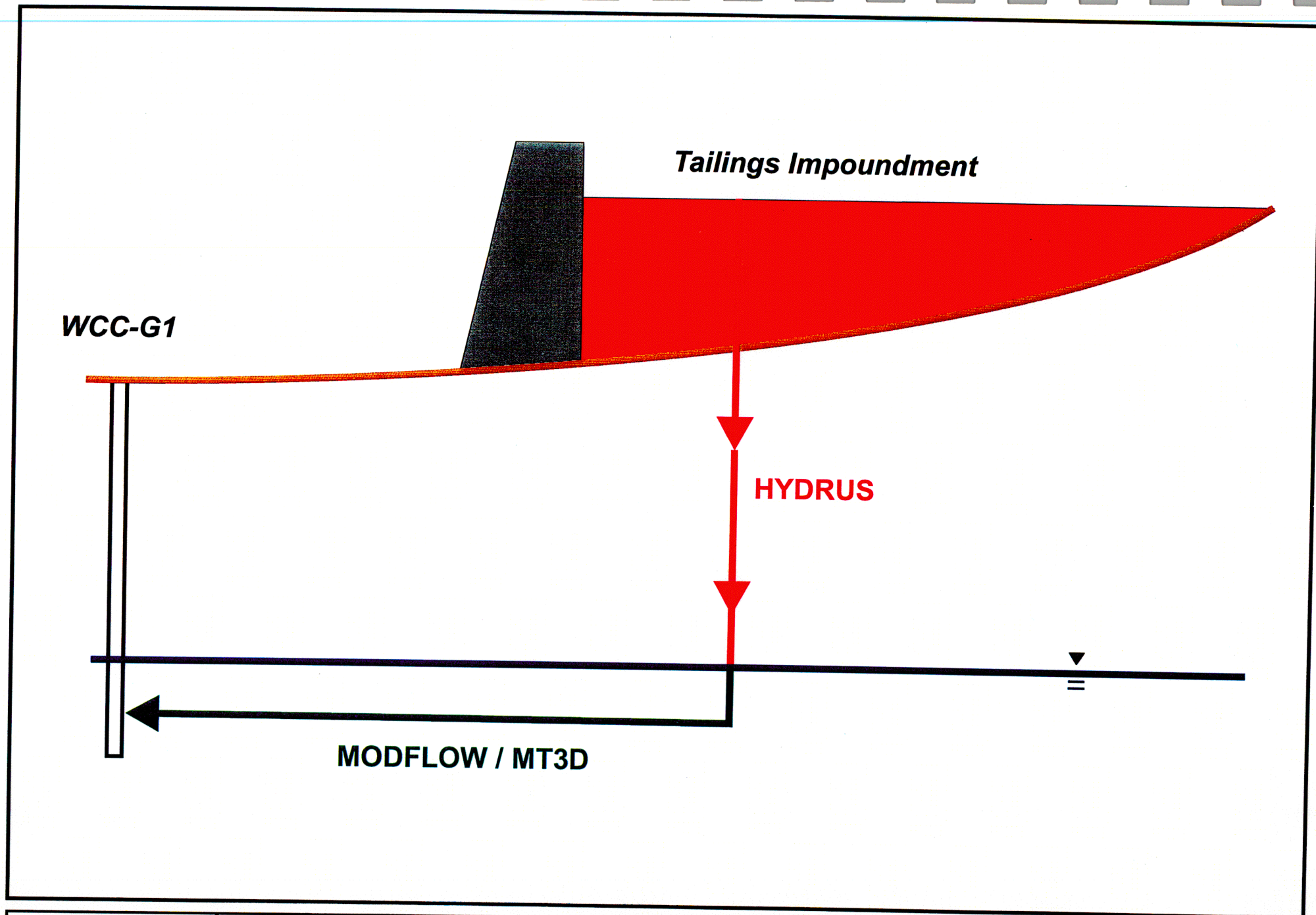
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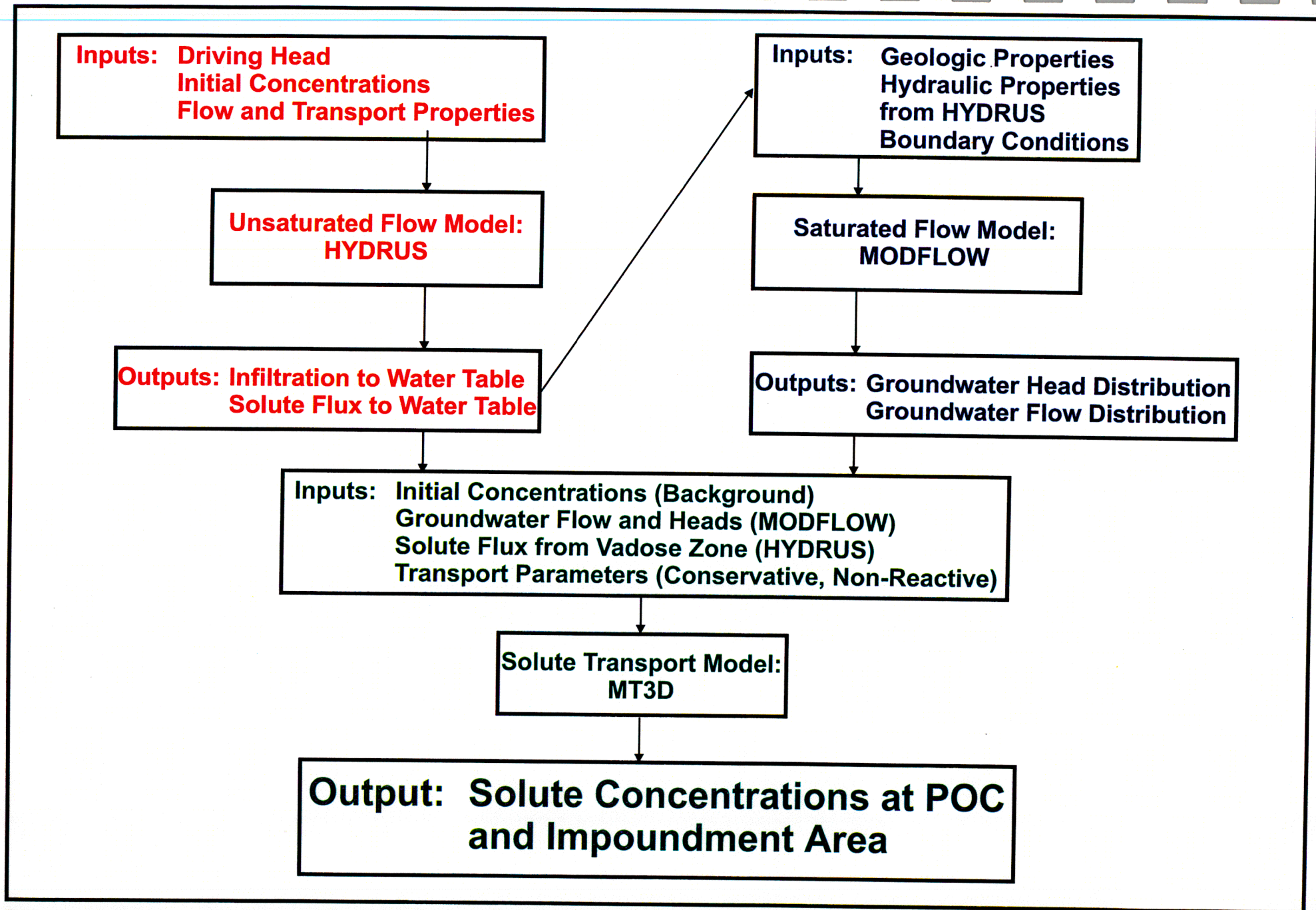
Figure 1-1. Giroux Wash Area





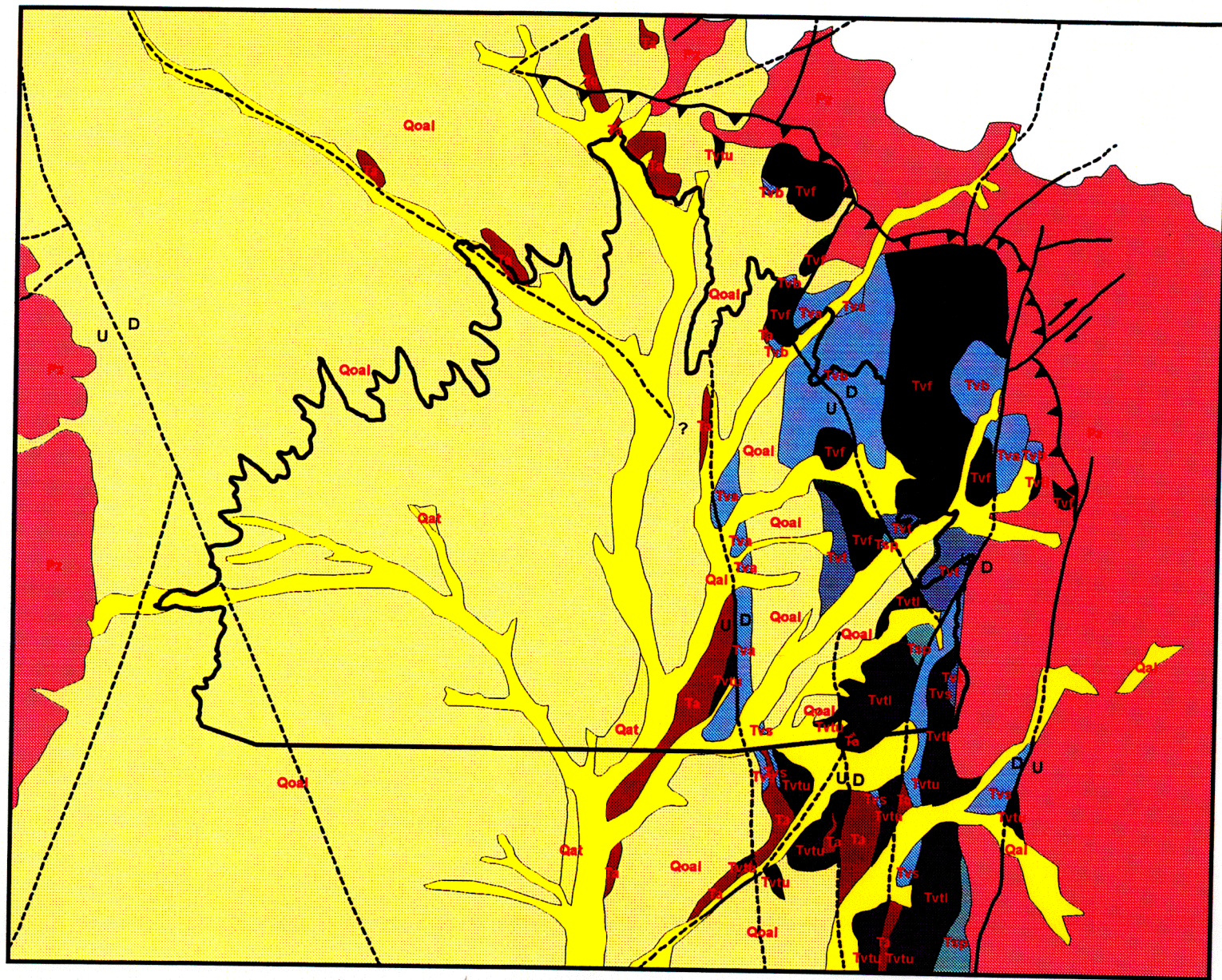
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Figure 1-2. Giroux Wash Modeling Approach.



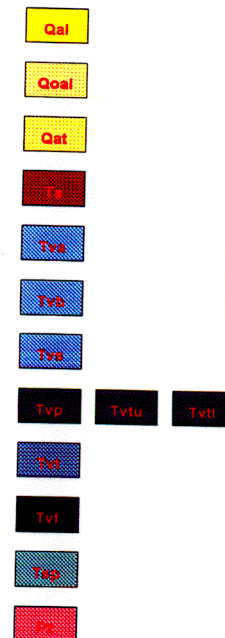
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Figure 1-3. Process Flow Diagram of Numerical Modeling.



LEGEND

- Inferred Normal Fault
- - - Concealed Normal Fault
- ▲ Thrust Fault (saw teeth on upper plate)



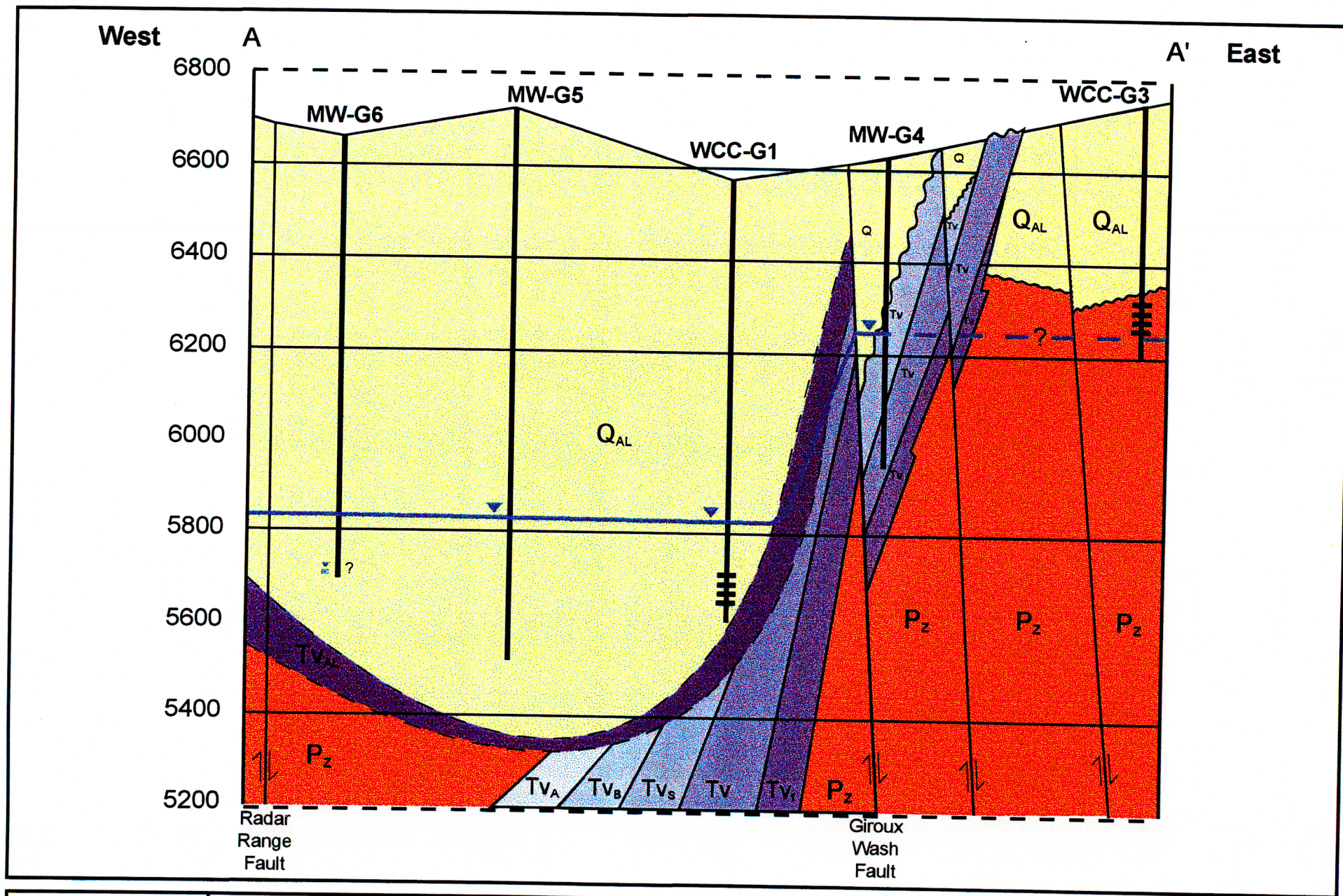
2000 0 2000 4000 Feet

Show wells from Fig 2-3

Figure 2-1. Geologic Map of Giroux Wash Area

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8/4/97





Generation

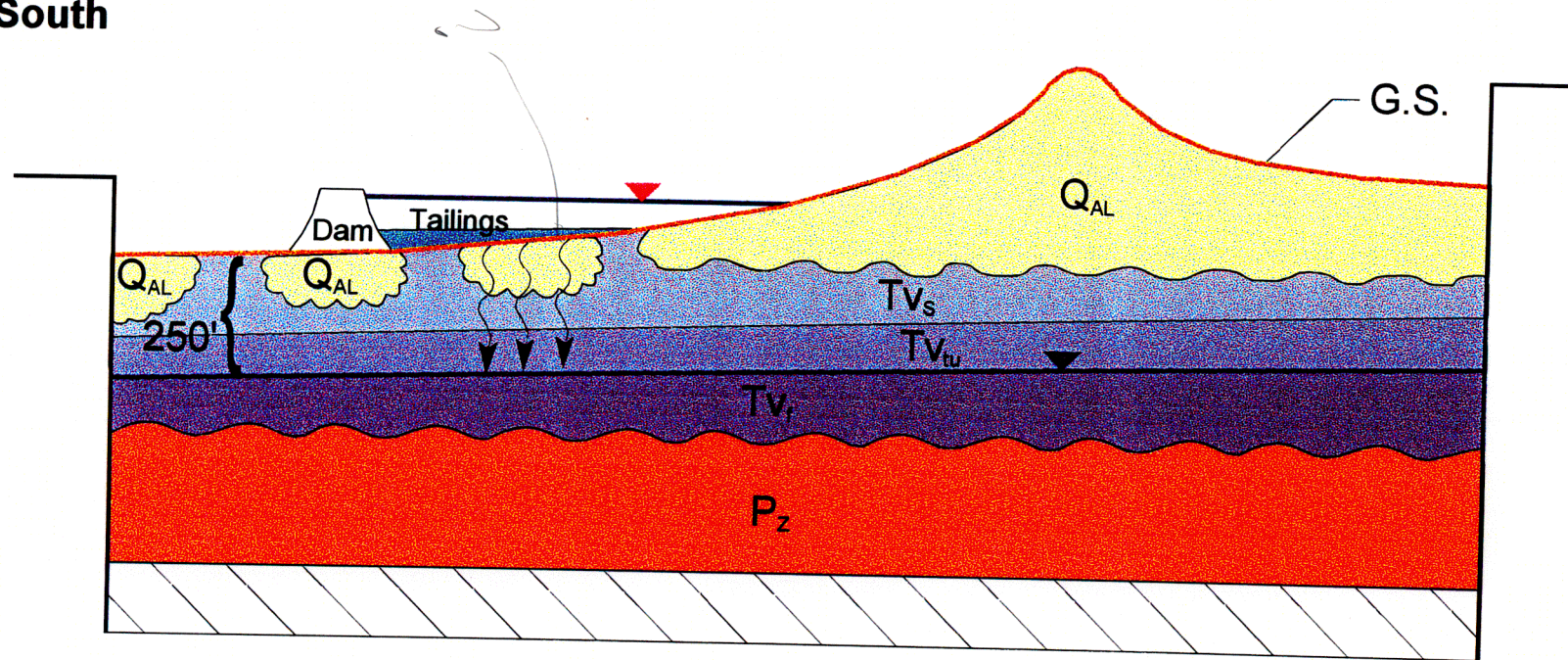
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Figure 2-2. Geologic Cross-Section (East-West) Beneath Impoundment.



Eastern Portion
South

North

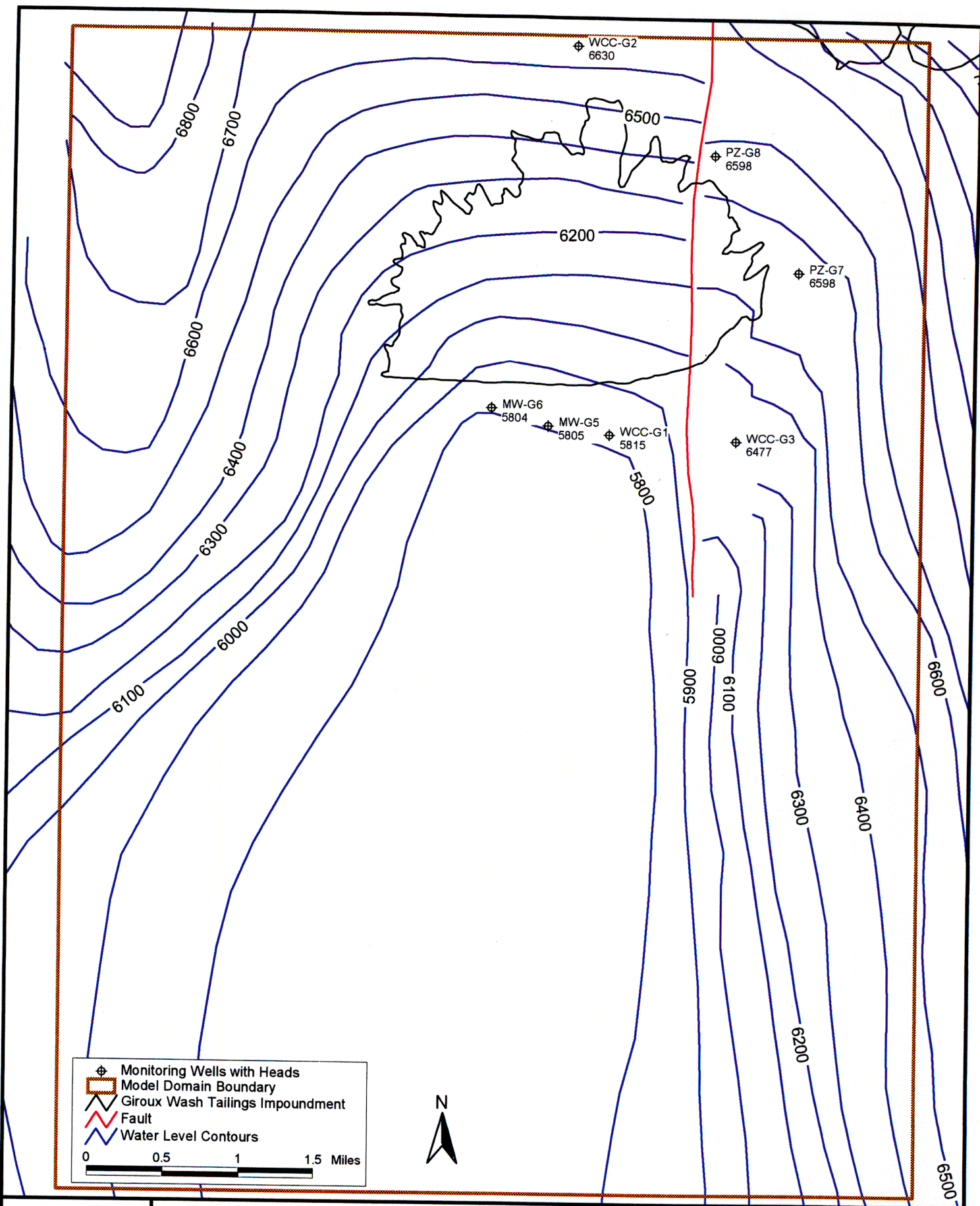


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8/4/97

Figure 2-3. Geologic Cross-Section (South-North) Beneath Impoundment.

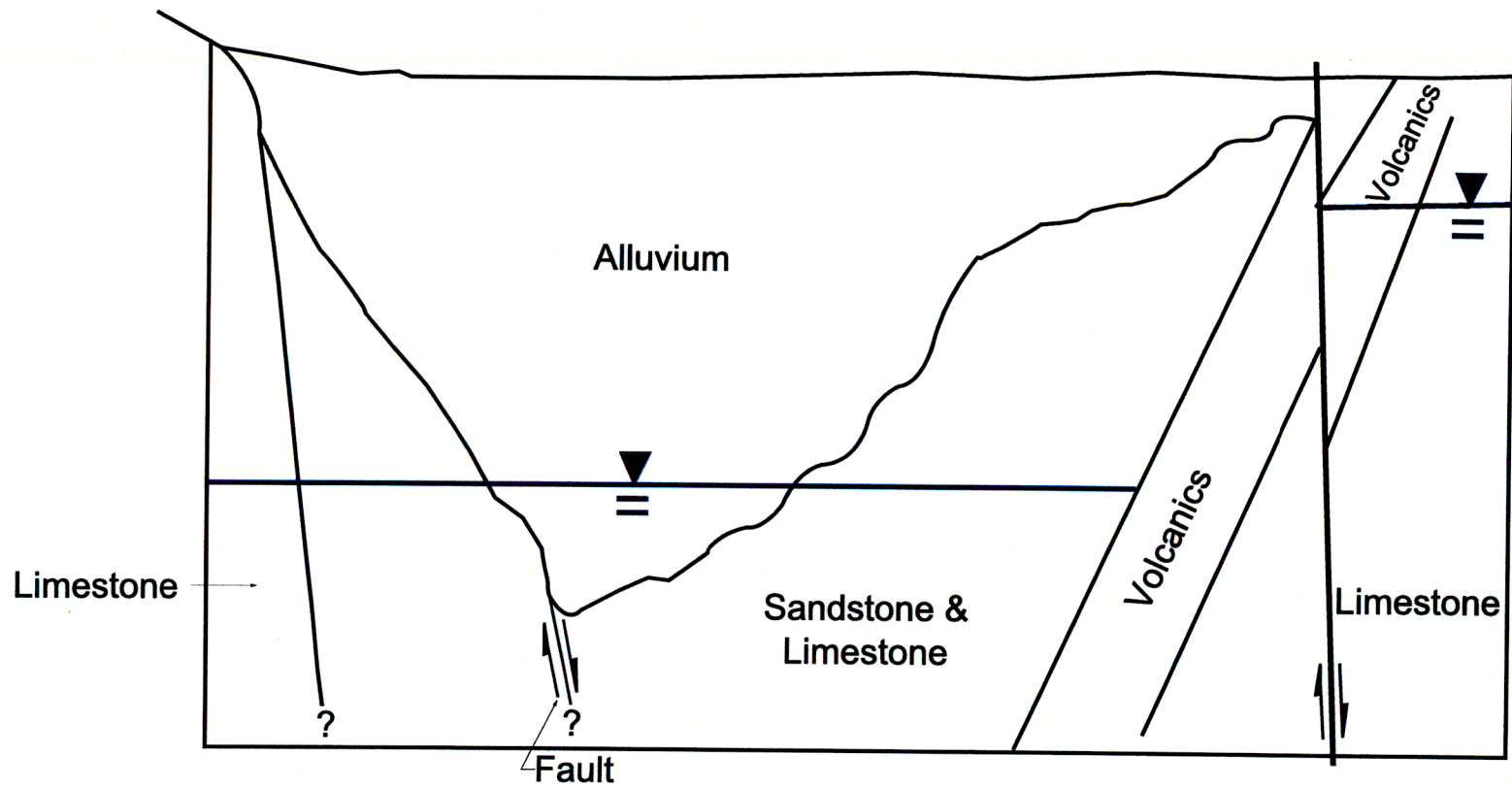

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Generation
Date:
8/6/97

Figure 3-1. Approximate Water Table Map.

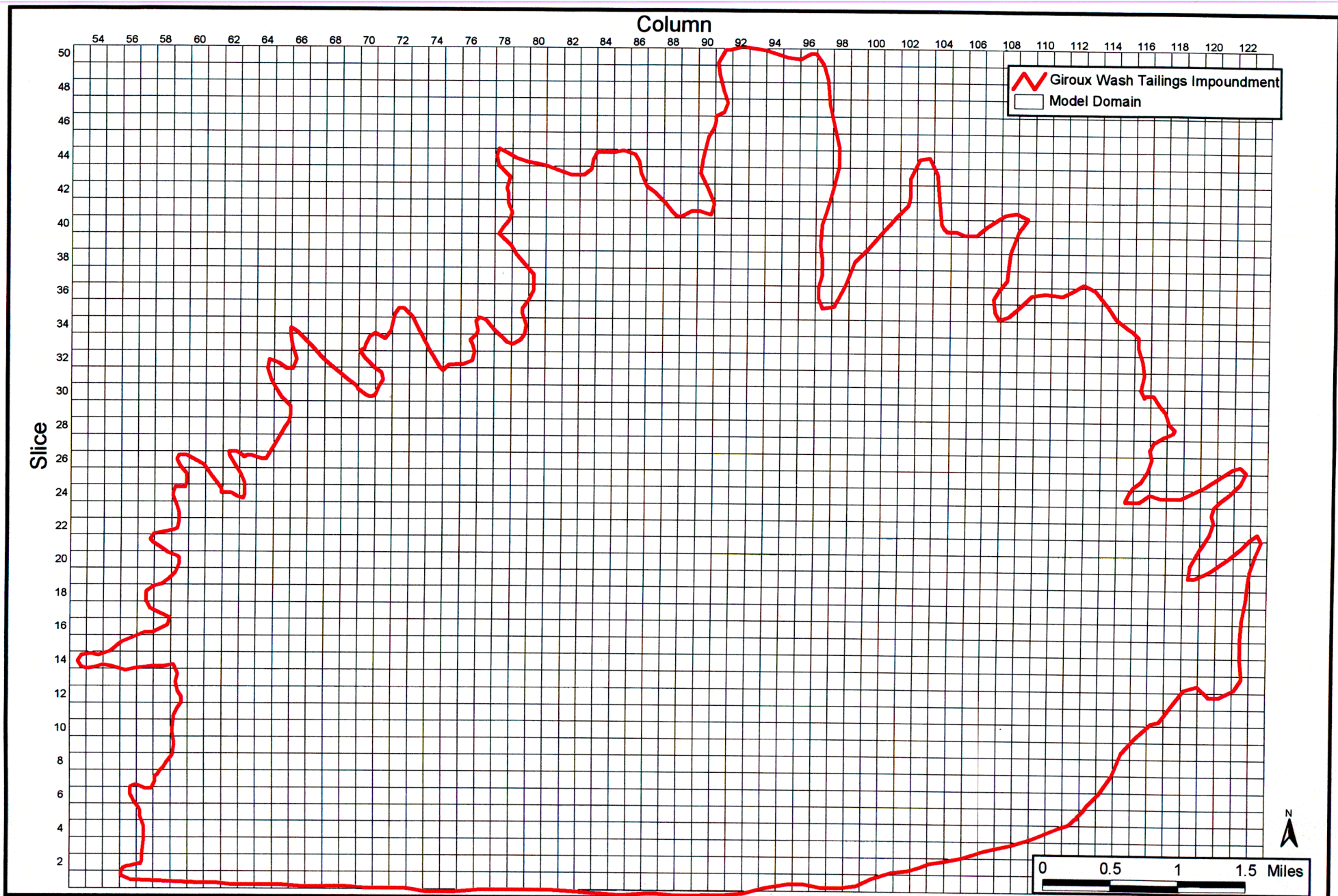




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7/31/97

Figure 4-1. Cross-Section of the Giroux Wash Vadose Zone.

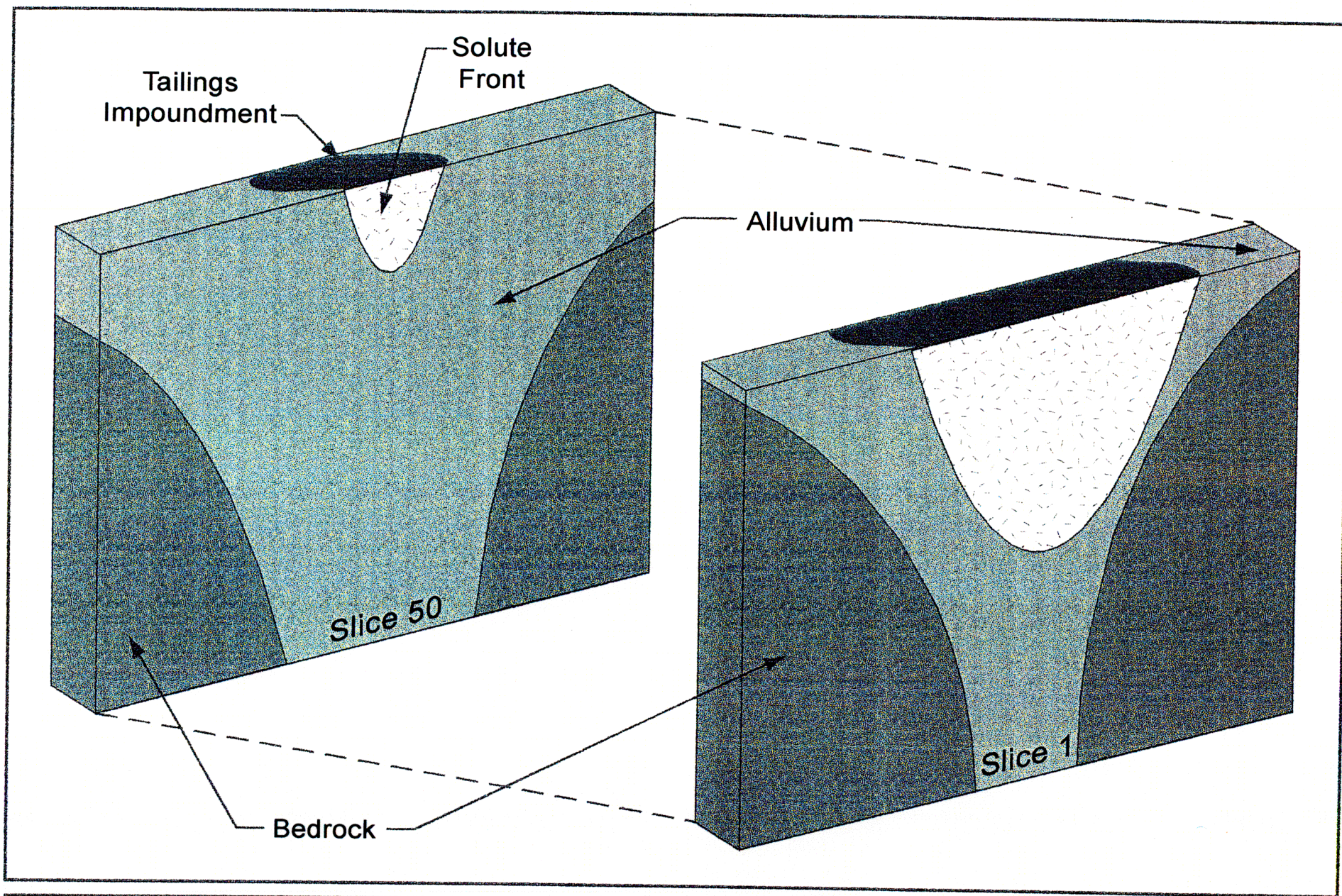




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Figure 4-2. Plan View of Unsaturated Zone Model Domain.
(200' x 200' Squares)


Geomega



Generation
Date:
7/31/97

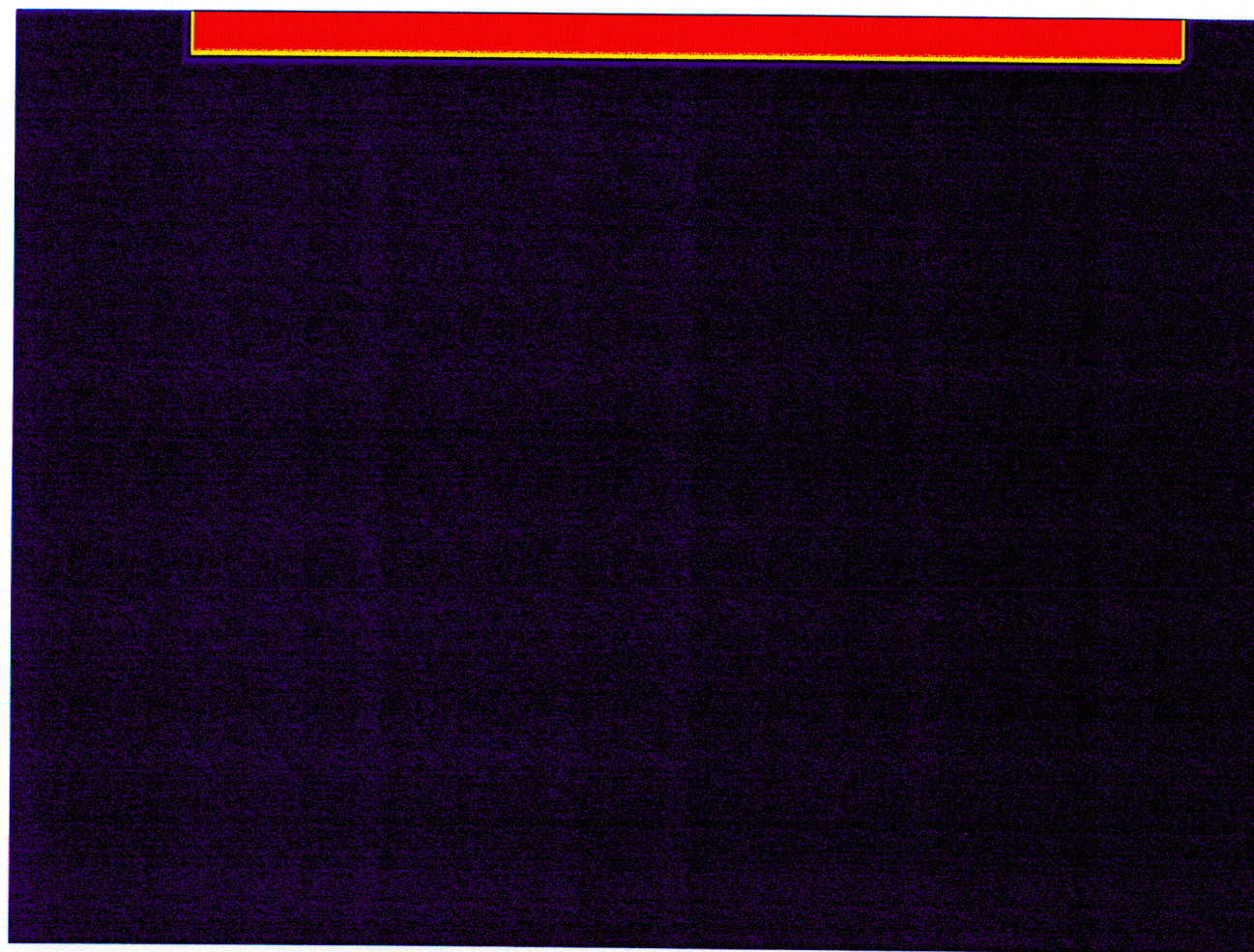
Figure 4-3. Conceptual Vadosose Zone Model.



Need for a

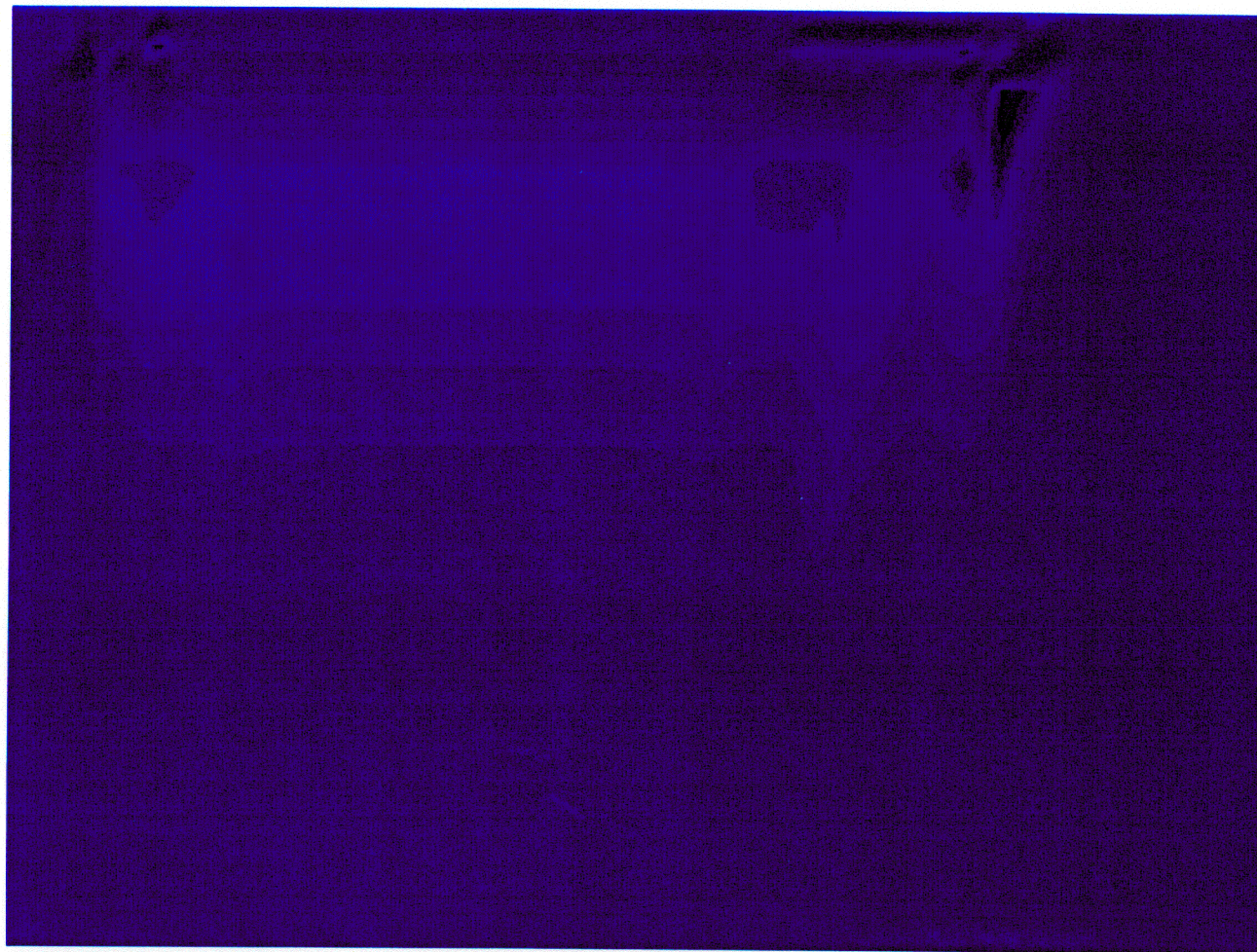
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7/31/97

Figure 4-4. Model Domain Cross-Section
(Vertical Exaggeration 1:0.075).



Generation
Date:
7/31/97

Figure 4-5. Solute Concentration at $t = 0$
(Vertical Exaggeration 1:0.075).

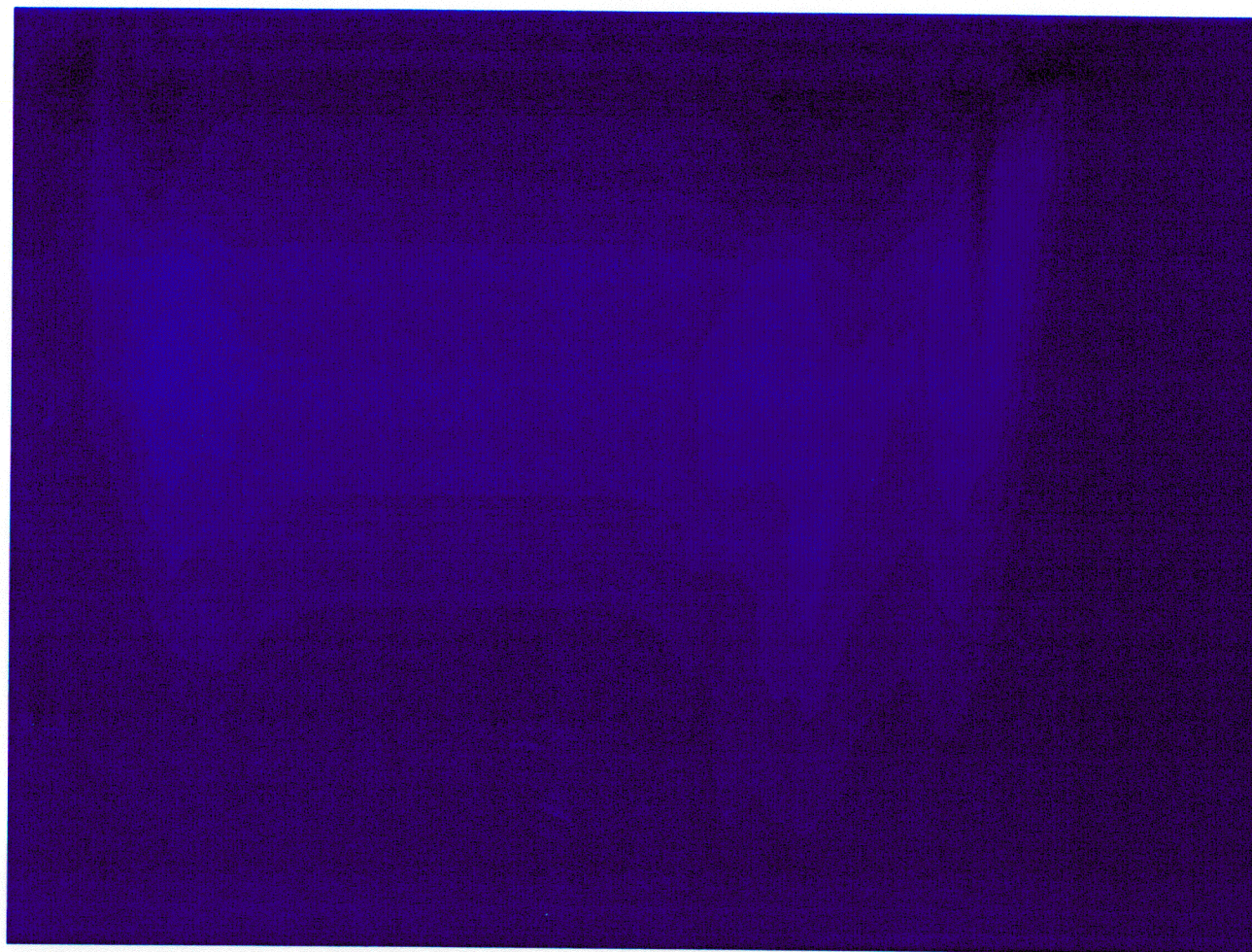


Solute
16 Years

Generation
Date:
7/31/97

Figure 4-6. Solute Concentration at $t = 16$ Years
(Vertical Exaggeration 1:0.075).

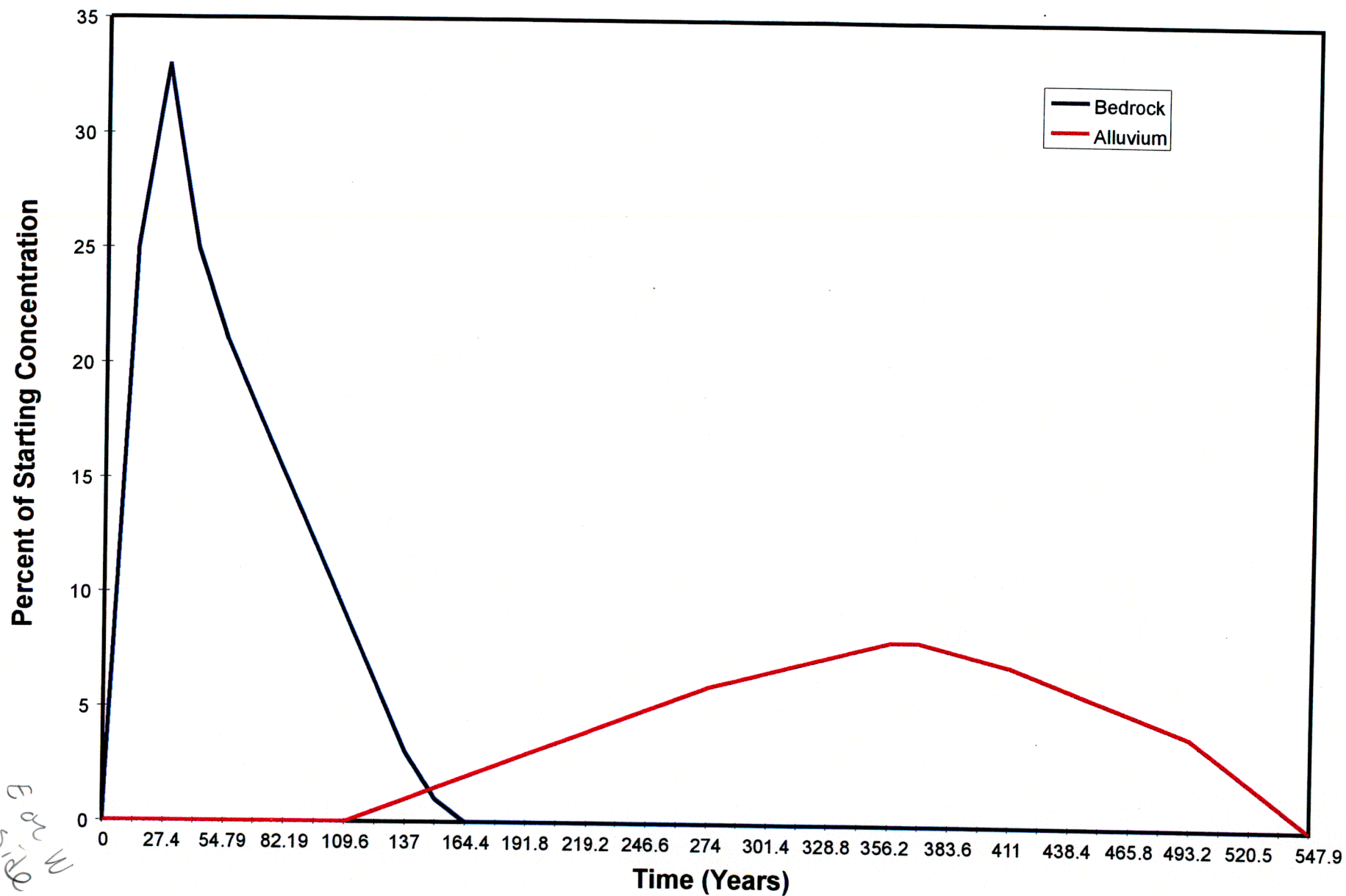

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Generation
Date:
7/31/97

Figure 4-7. Solute Concentration at $t = 100$ Years
(Vertical Exaggeration 1:0.075).

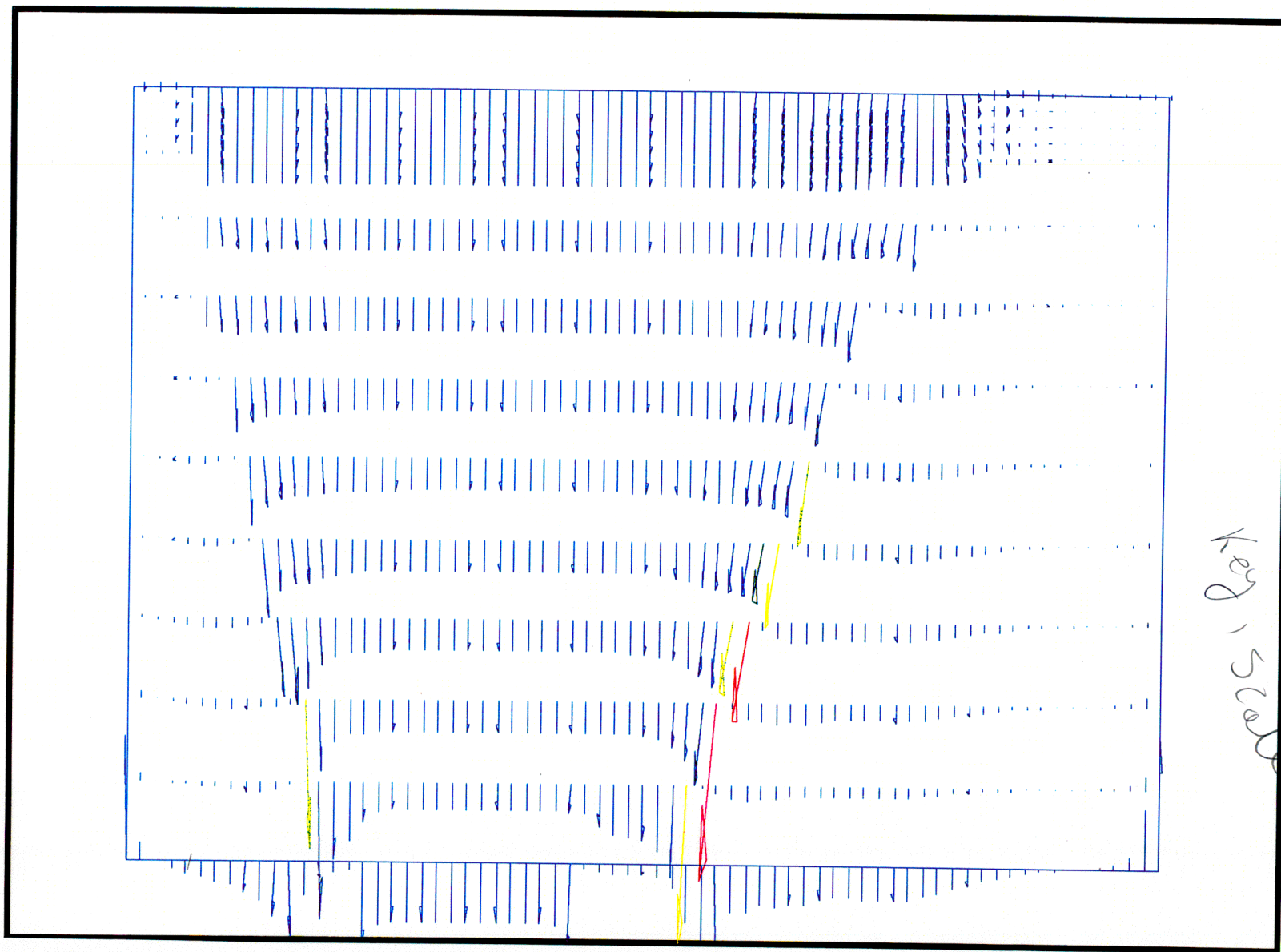

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Generation
Date:
7/31/97

Figure 4-8. Solute Discharge to Groundwater.

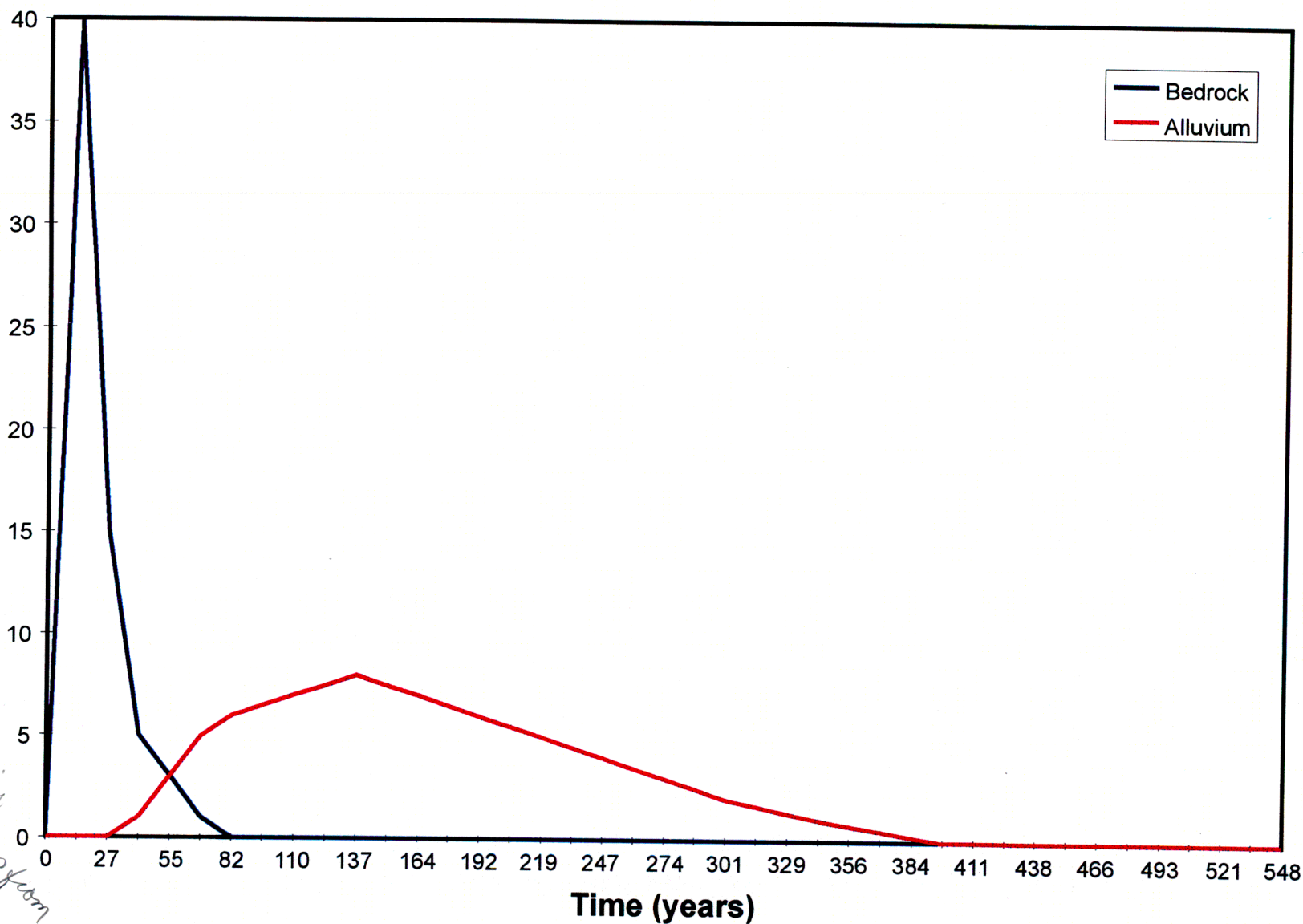




Generation
Date:
7/31/97

Figure 4-9. Predicted Flow Field
(Vertical Exaggeration 1:0.075).

Percent of Starting Concentrations

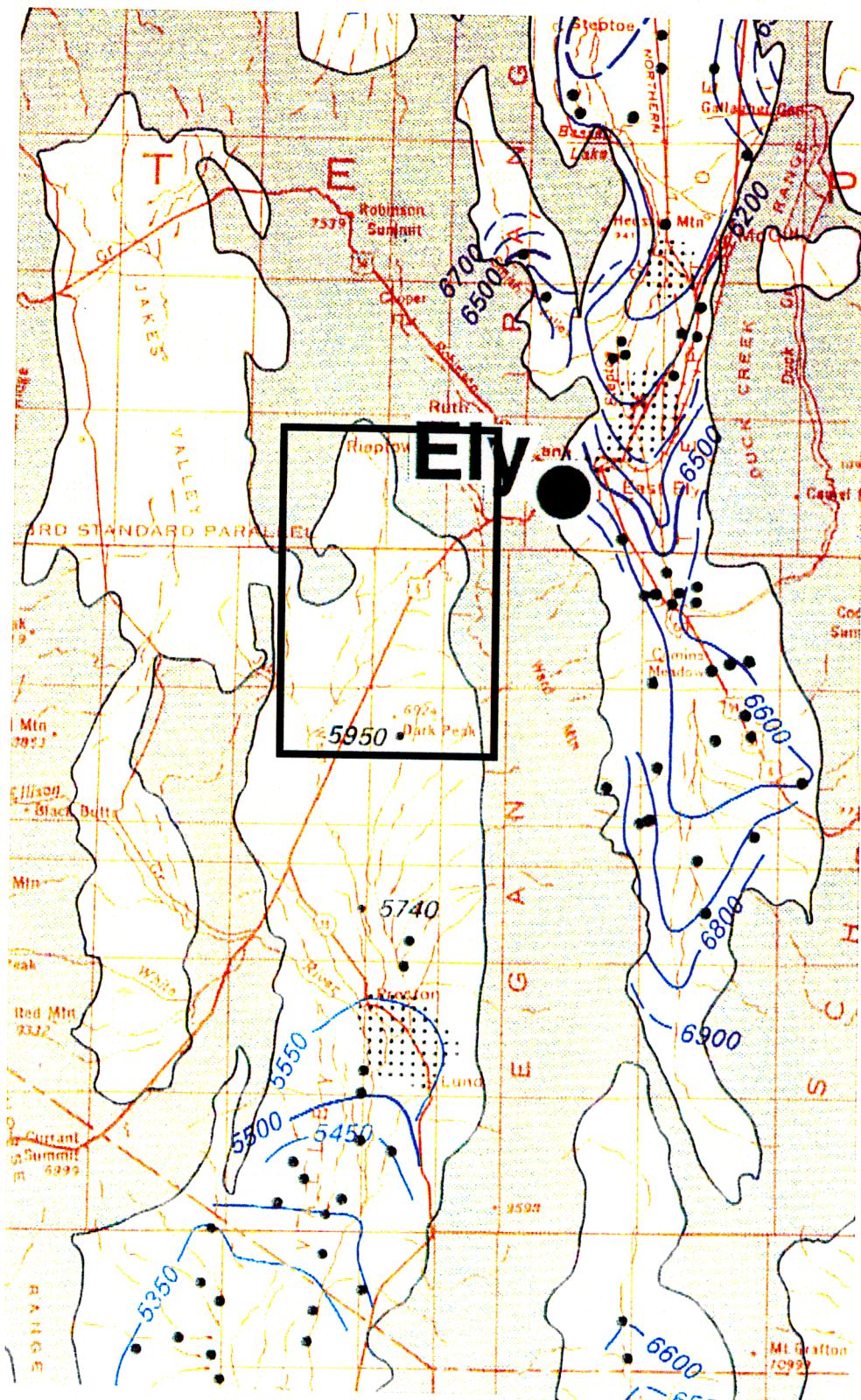



explain
but curves from
4-8 for comparison

Generation
Date:
7/31/97

Figure 4-10.Sensitivity Analyses.



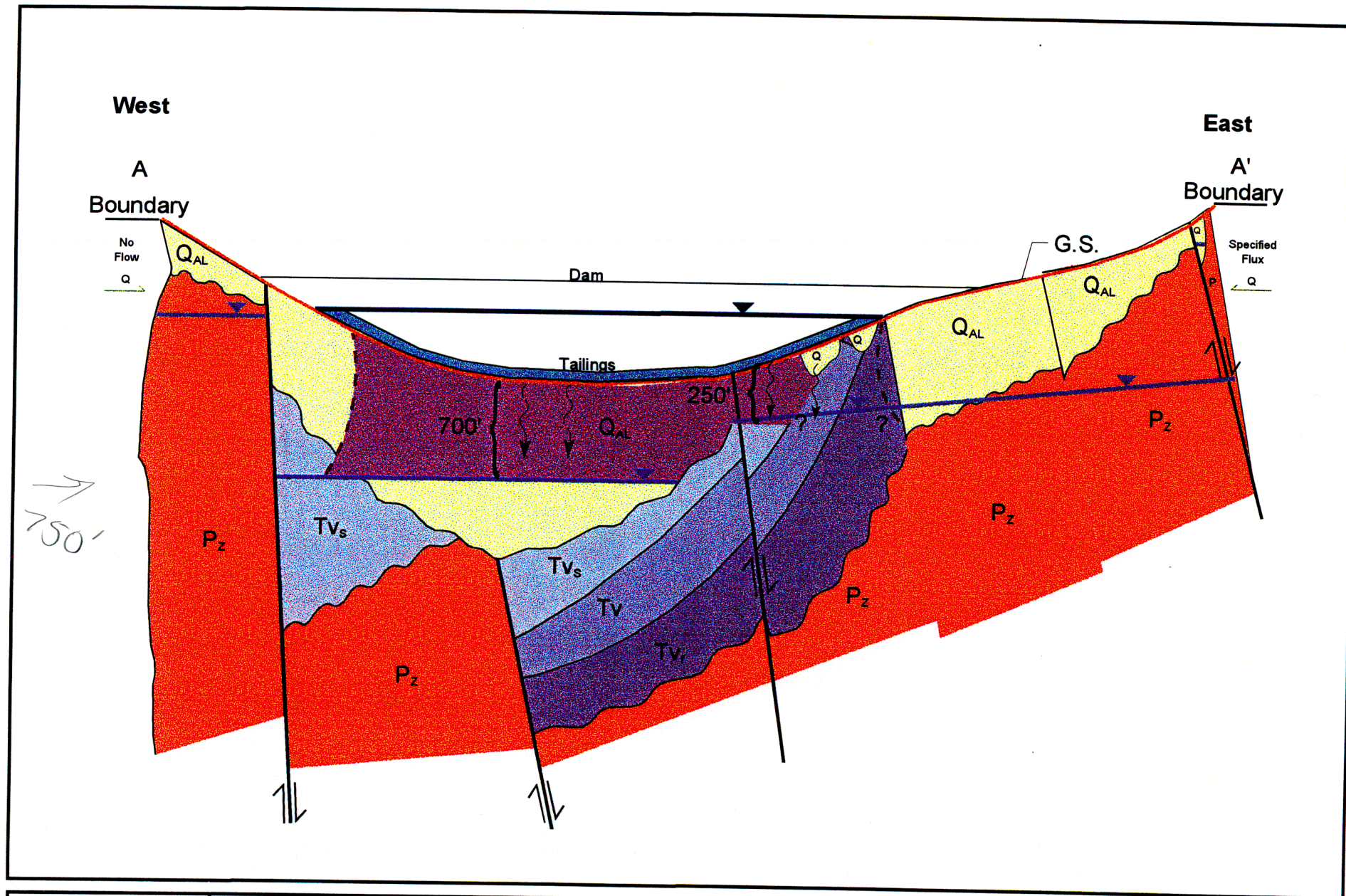


 FDM Model Domain

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8/7/97

Figure 5-1. Regional Water Table
(after Thomas et. al, 1986) and FDM Model Domain.





Generation
Date:
8/4/97

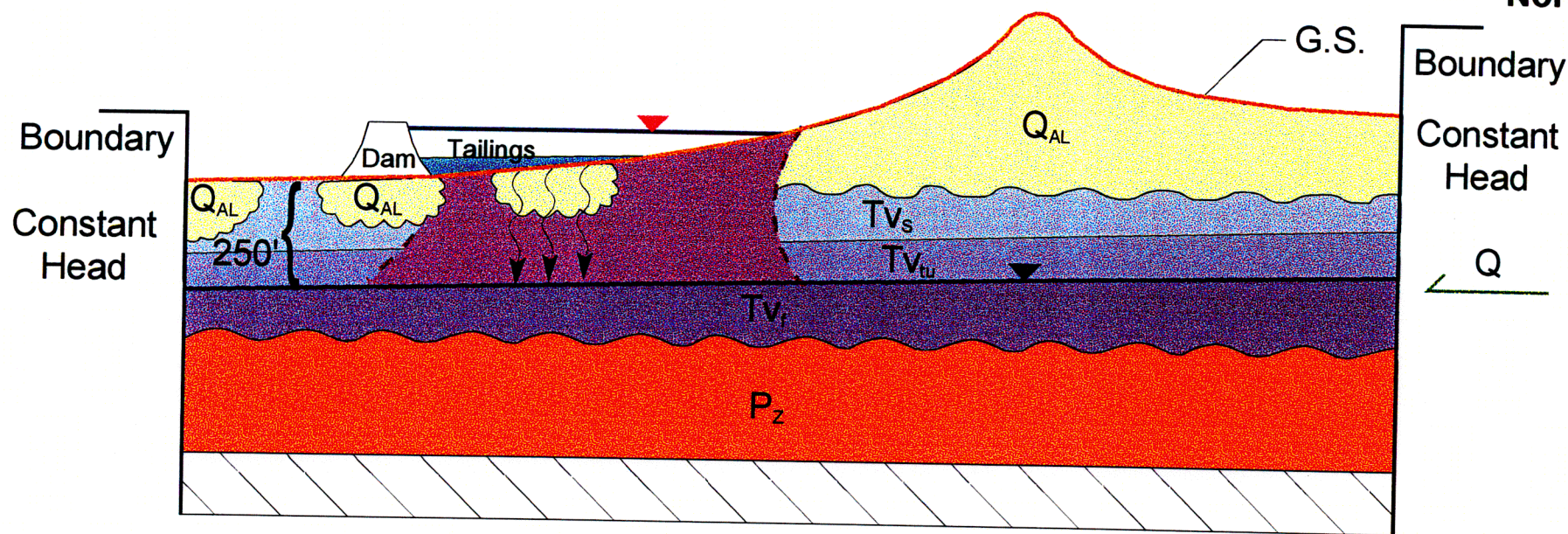
Figure 5-2. East - West Conceptual Flow Schematic.


Geomega

Eastern Portion

South

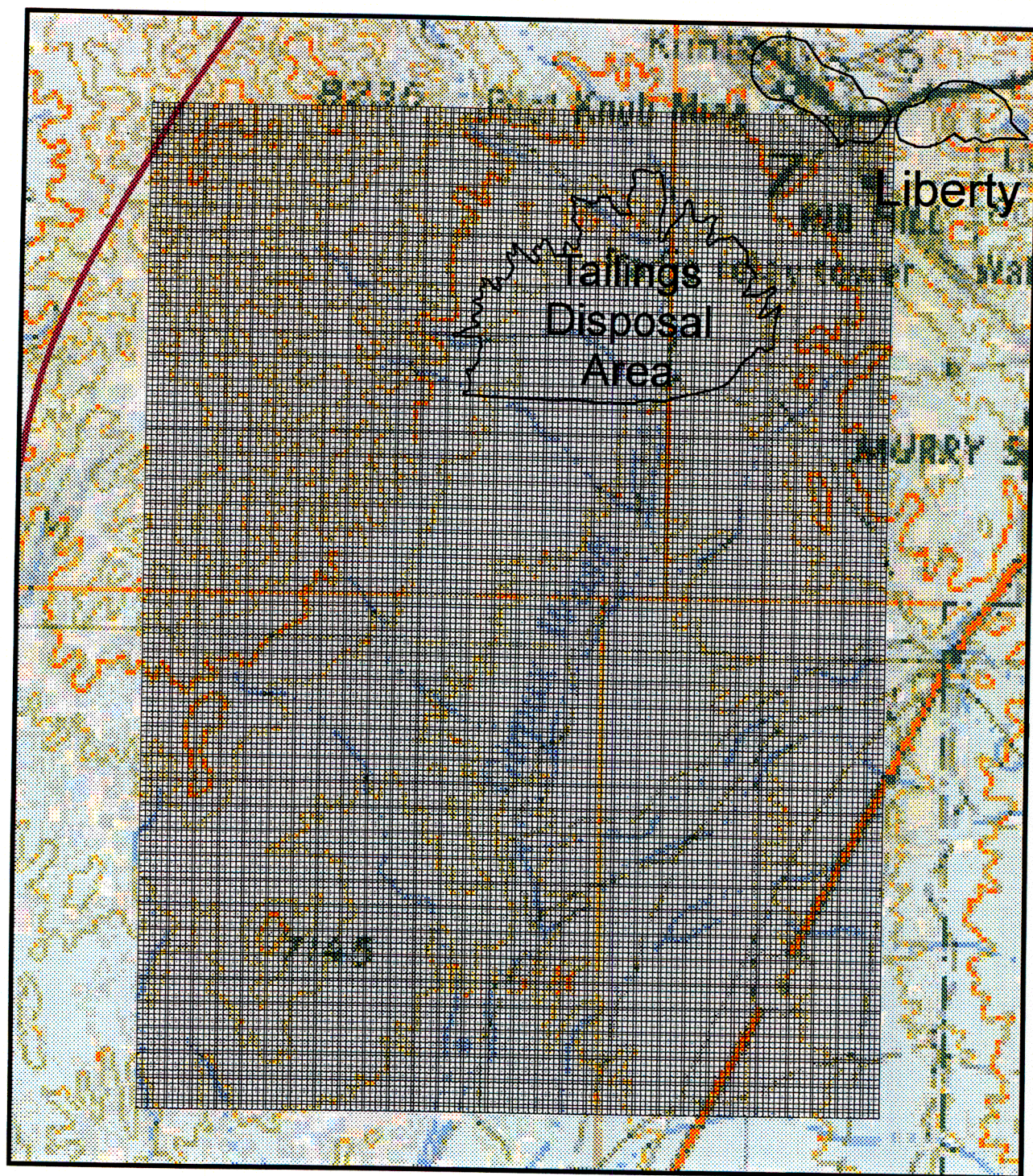
North



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8/4/97

Figure 5-3. North - South Conceptual Flow Schematic.

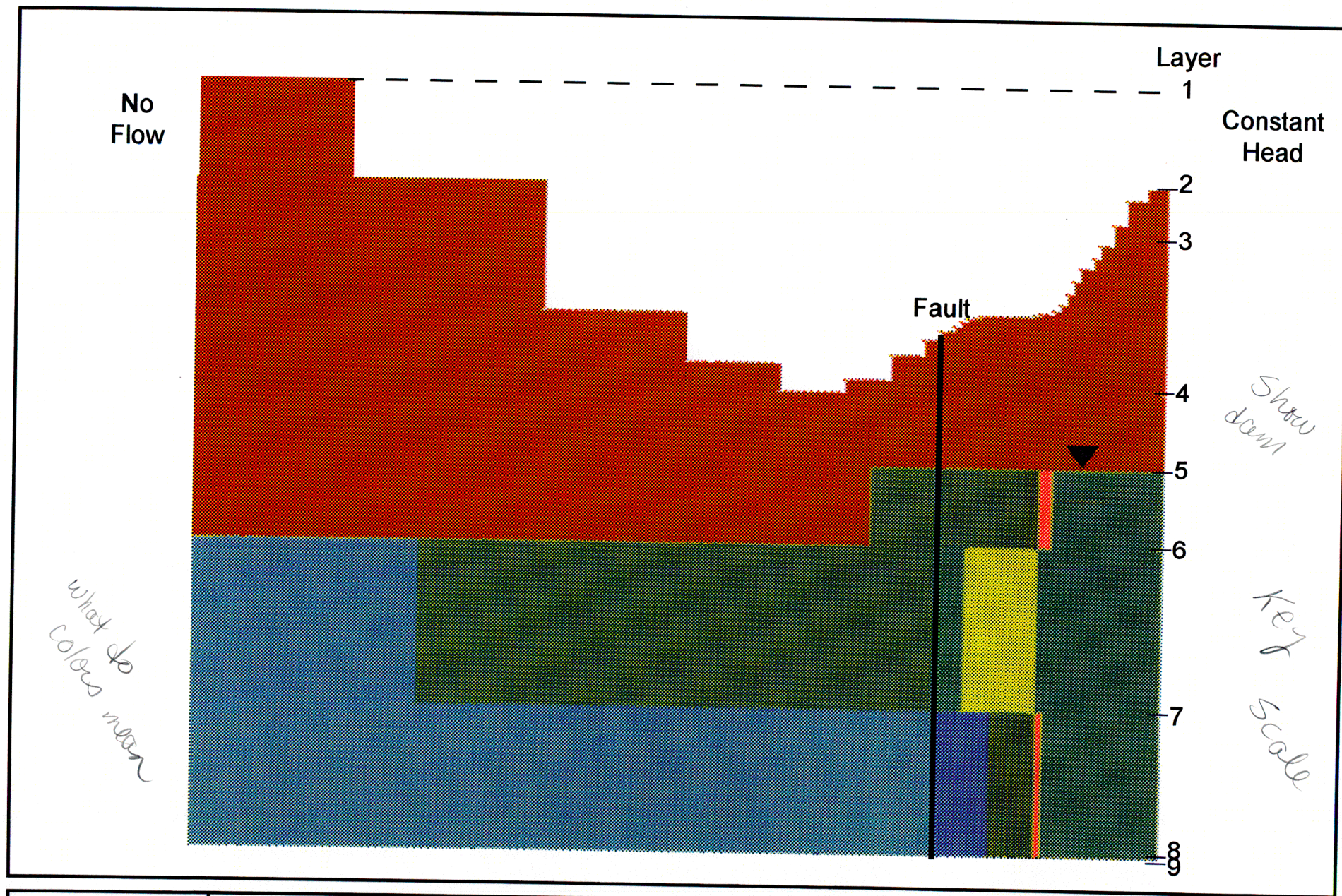

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8/4/97

Figure 5-4. Giroux Wash Impoundment
Finite Difference Model Grid.

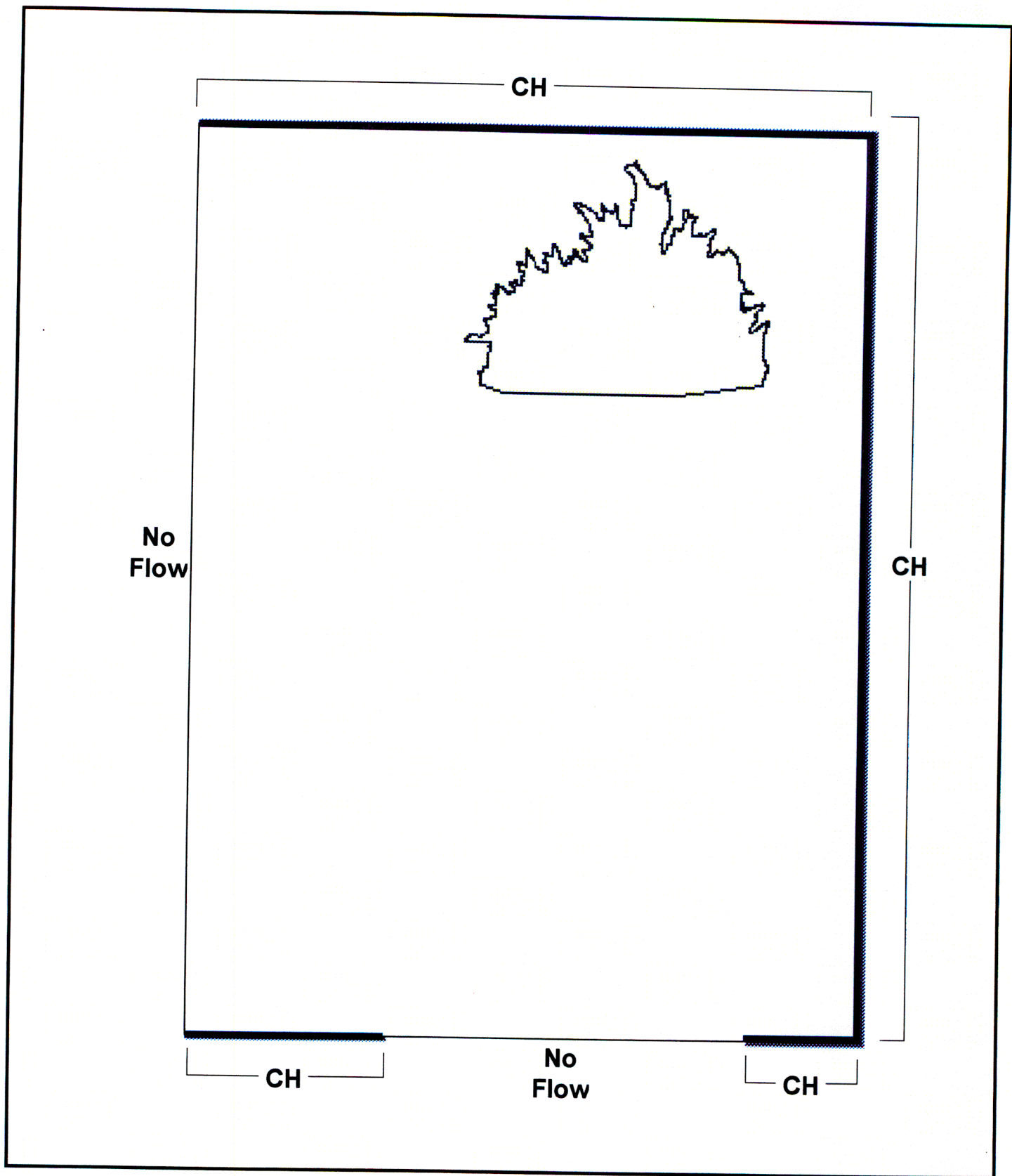

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Generation
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8/5/97

Figure5-5. Finite Difference Model Discretization, Section View.

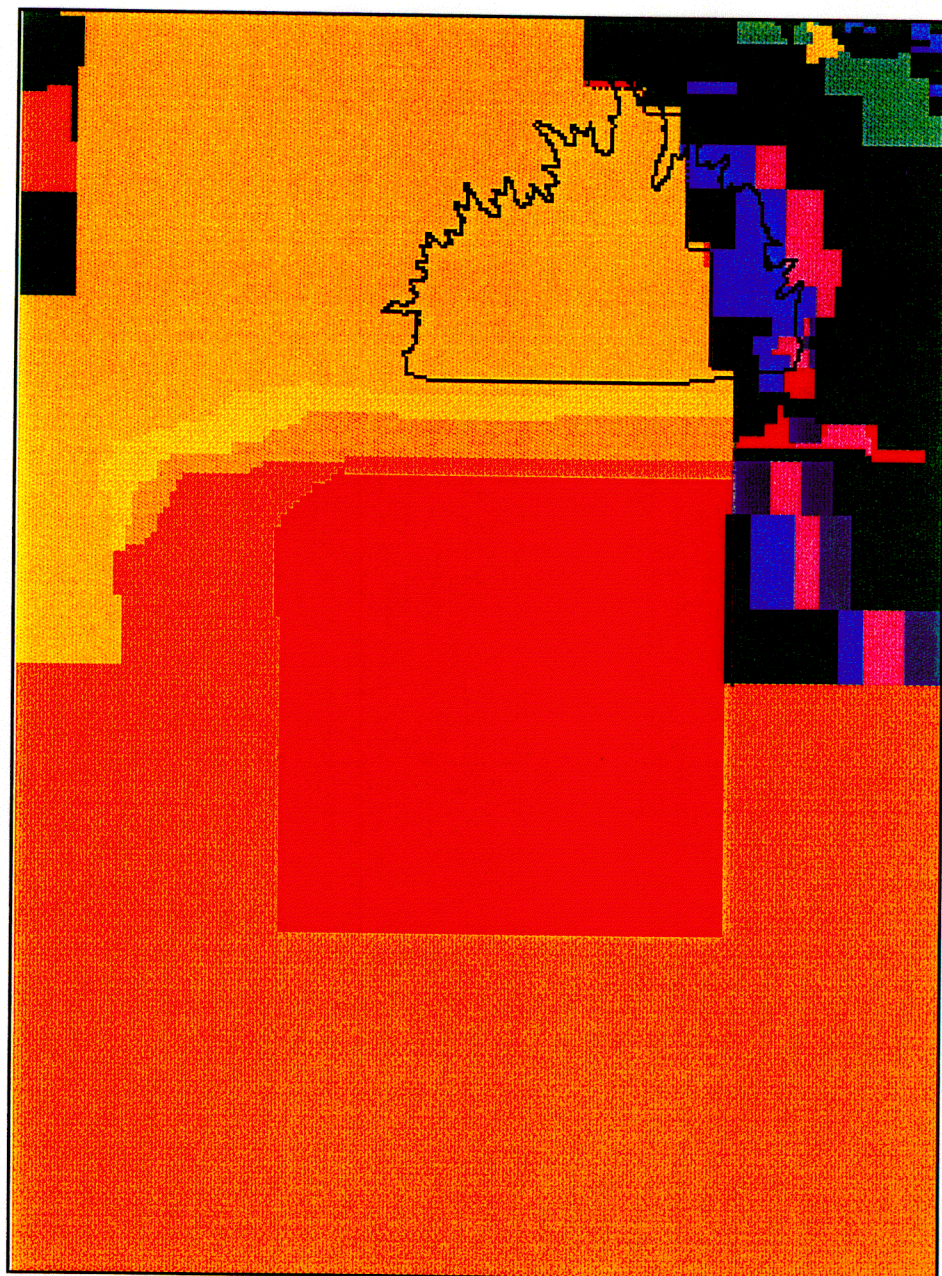
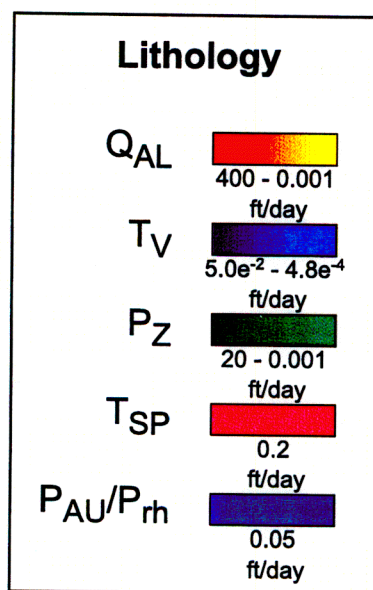




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8/5/97

Figure 5-6. Boundary Conditions
Assigned, Layer 6.

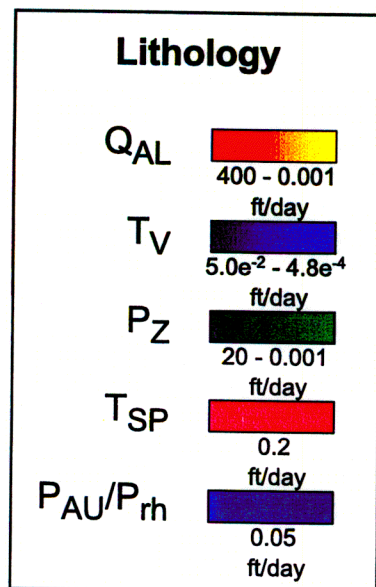

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8/6/97

Figure 5-7. Hydraulic Conductivity Distribution,
Layer 6.


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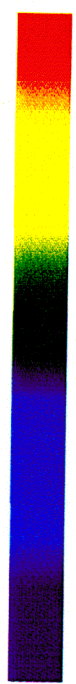
Generation
Date:
8/6/97

Figure 5-8. Hydraulic Conductivity Distribution,
Layer 7.

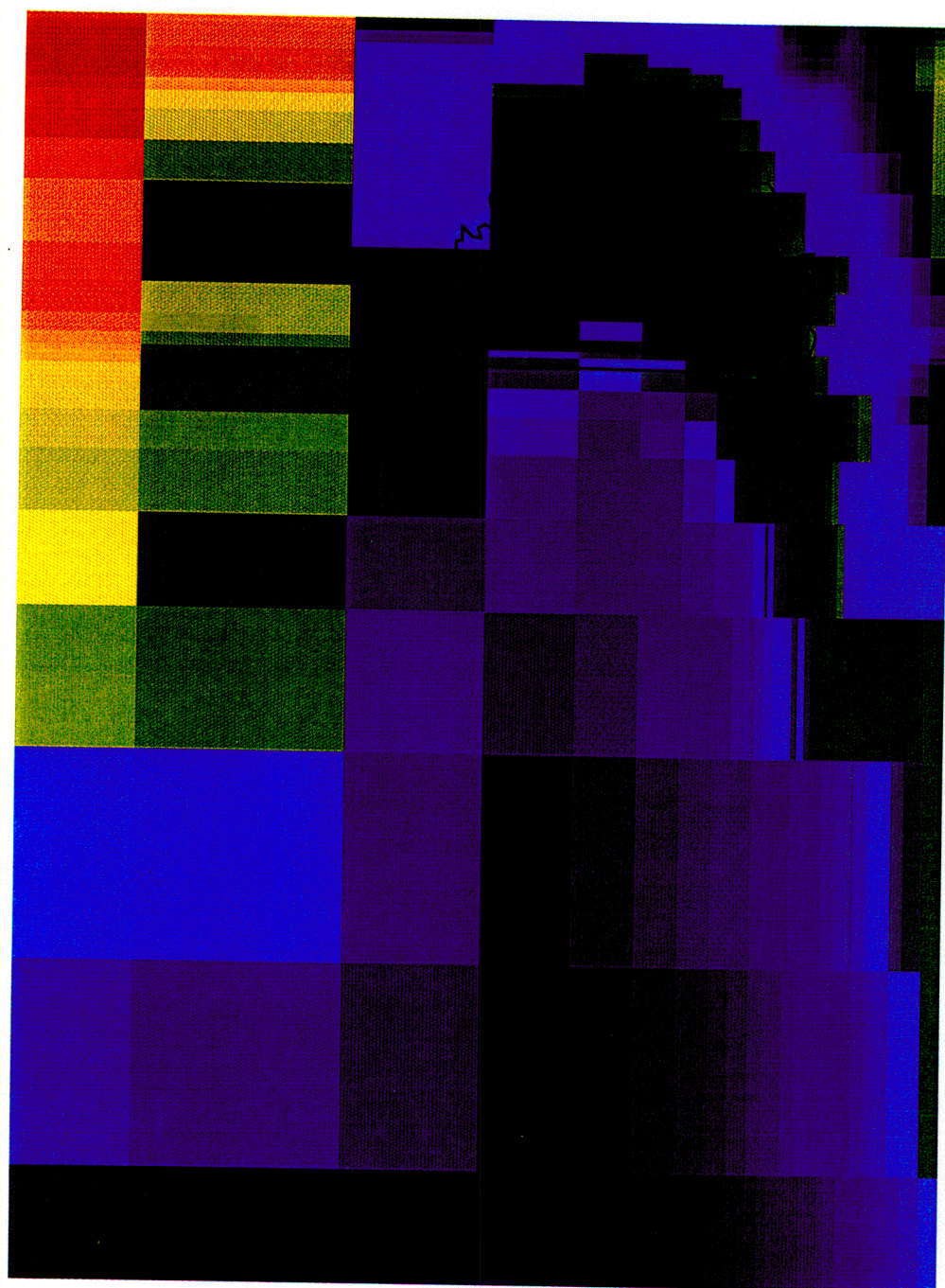
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R (in/yr)

10



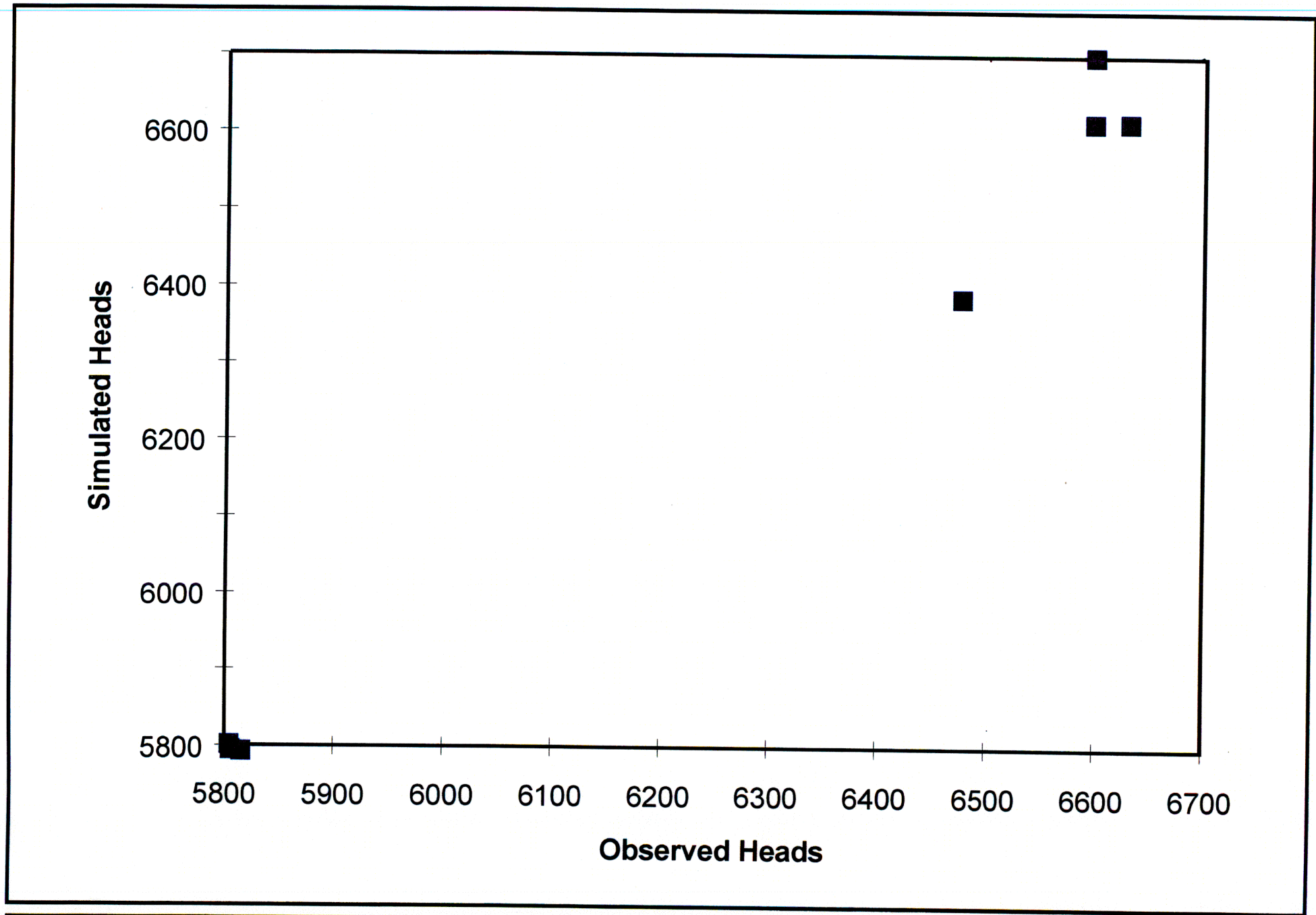
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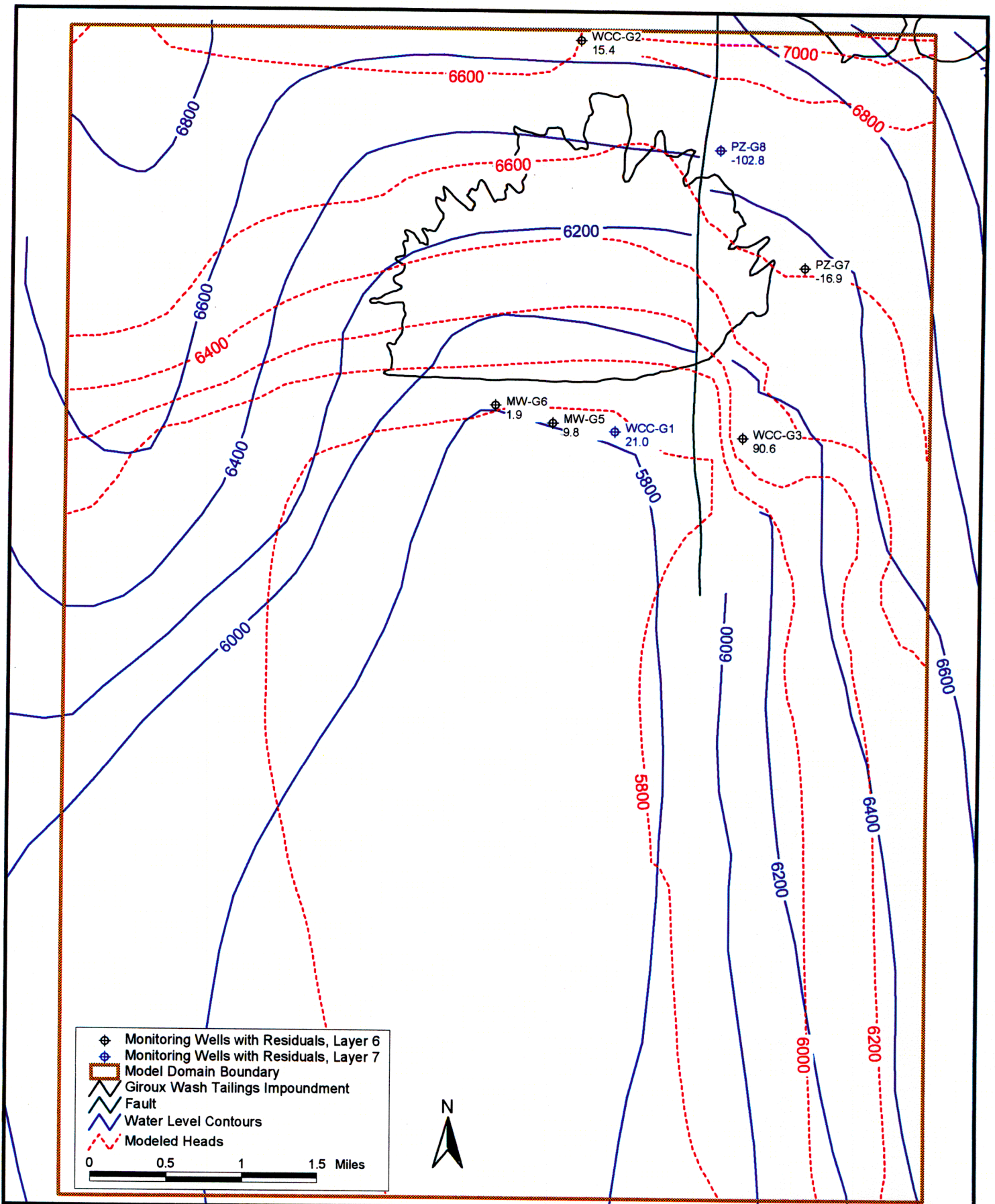
Figure 5-9. Recharge Rates Applied to
Top Active Model Layer.


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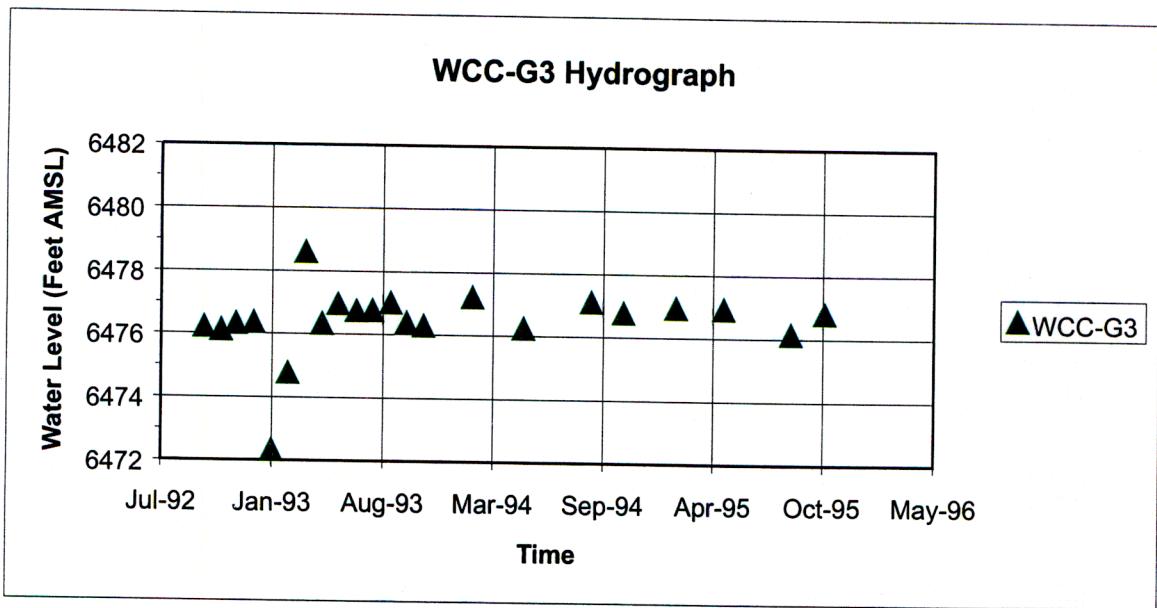
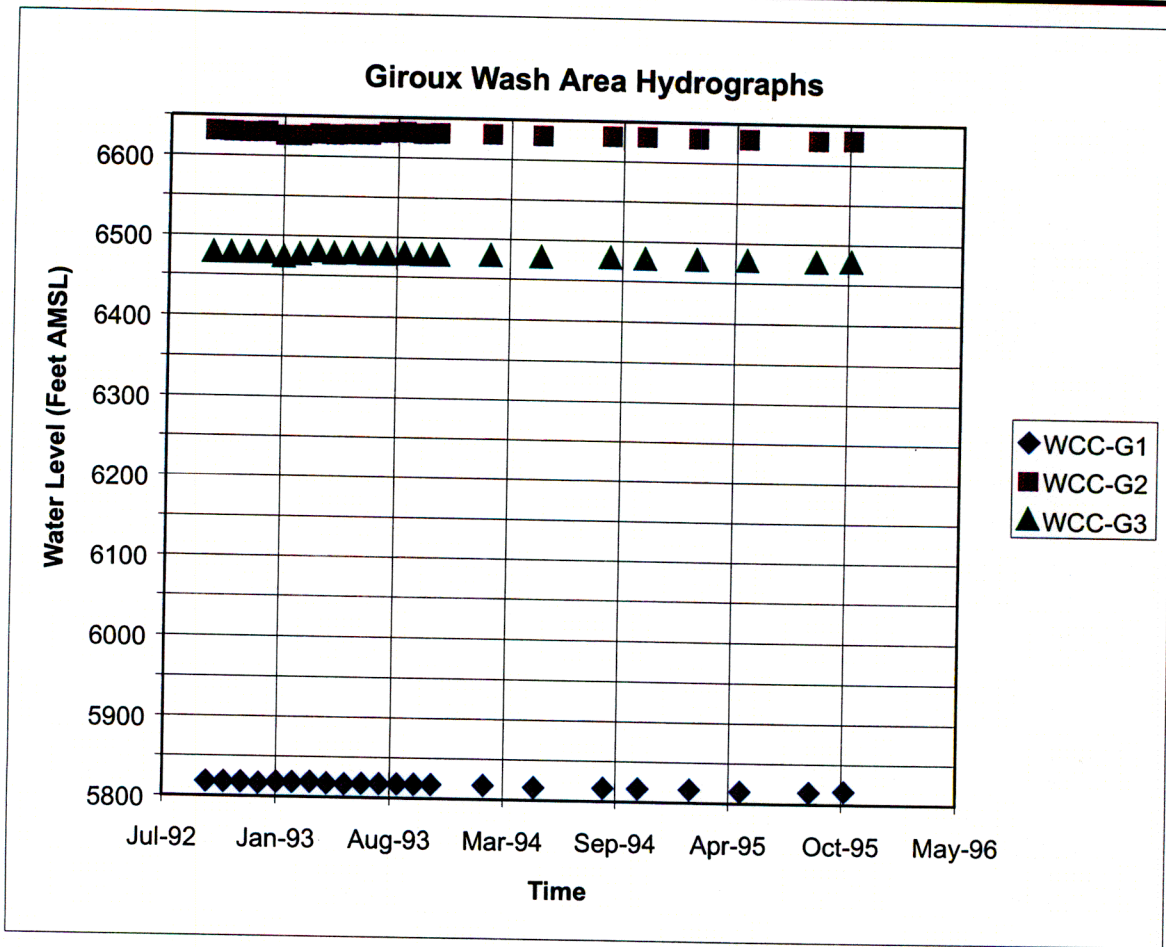
Figure 5-10. Calibrated Summary of S-S Flow Model.



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Figure 5-11.
 Observed vs. Predicted Water Table Map, Layer 6

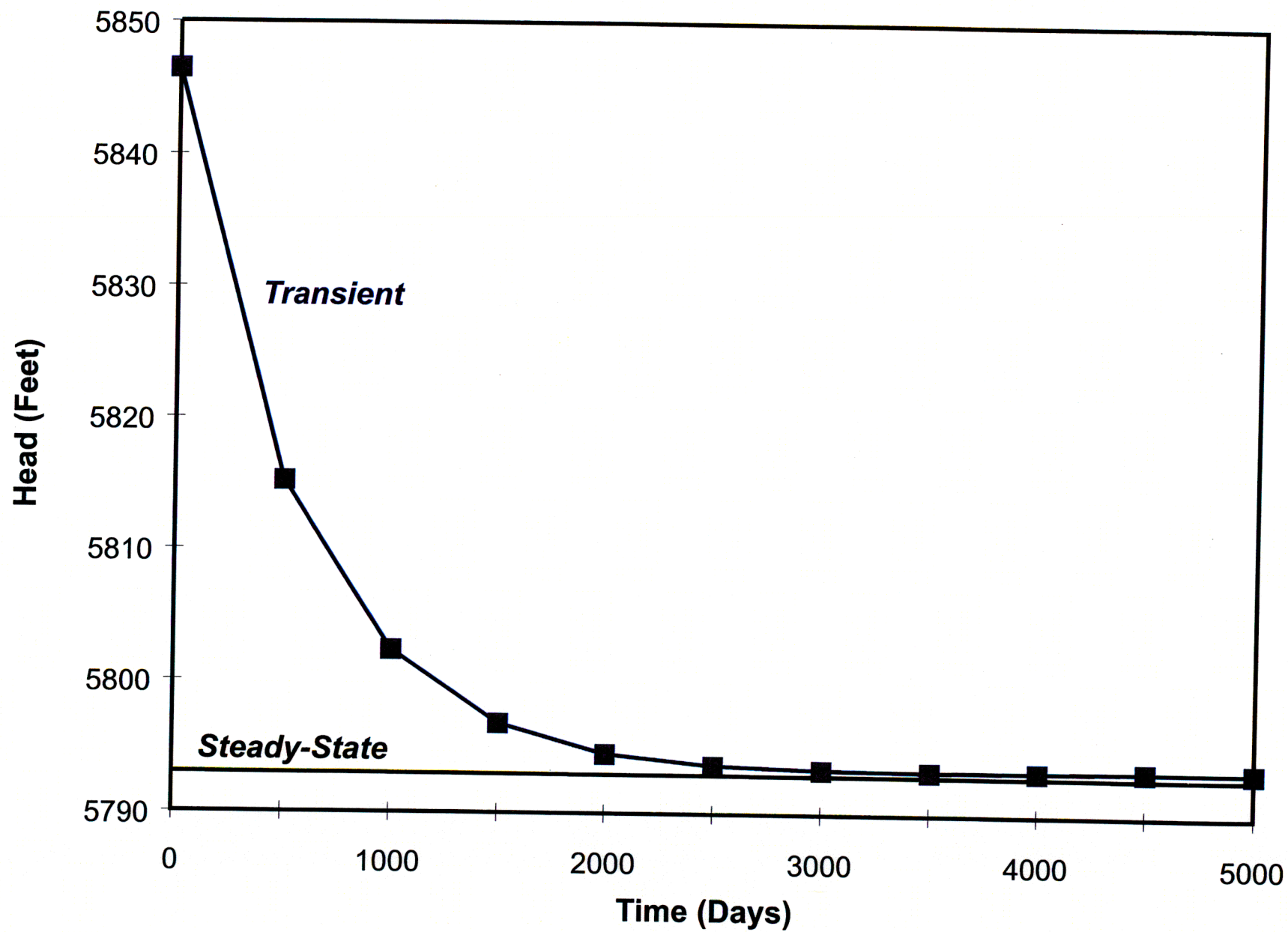




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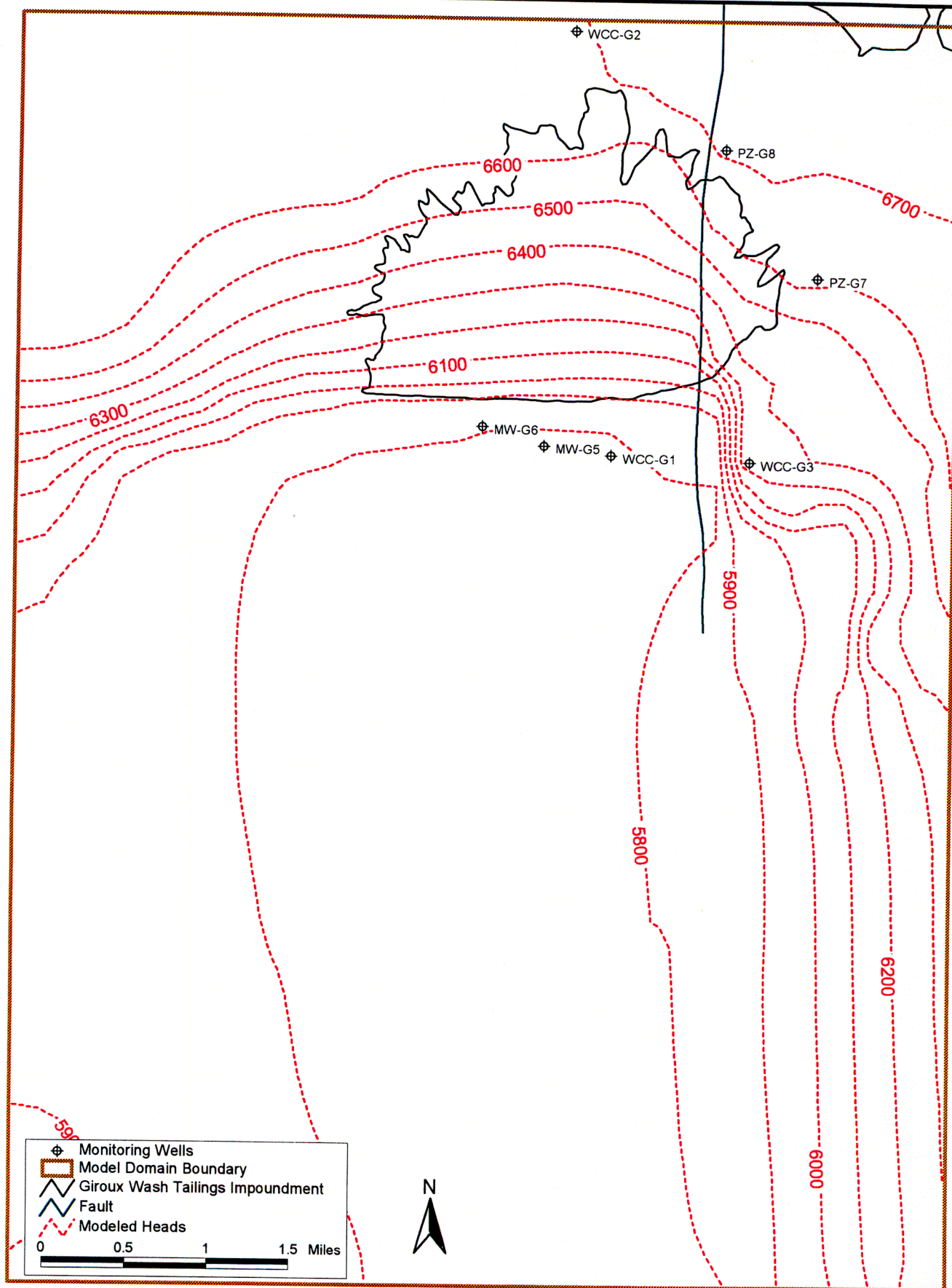
Figure 5-12.





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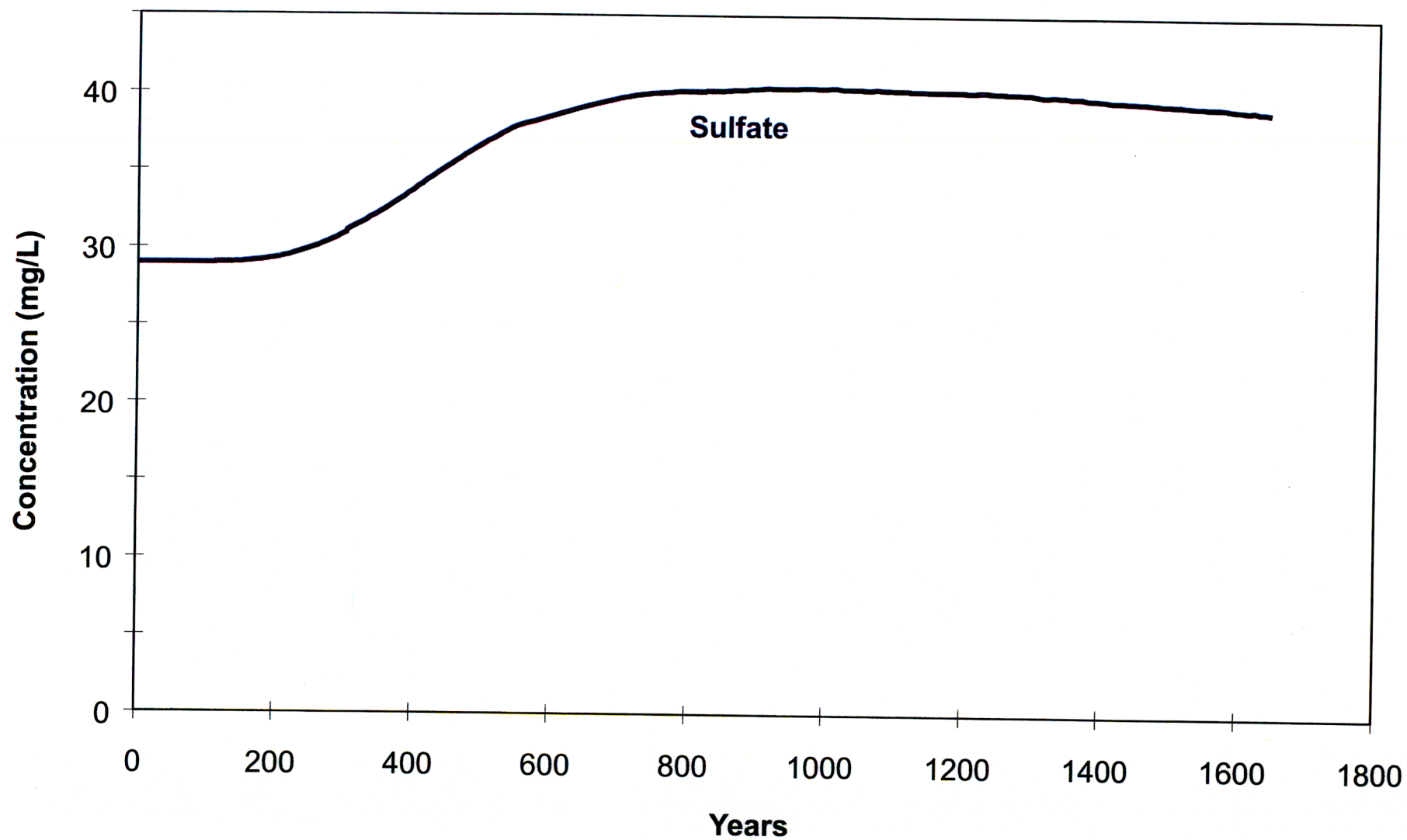
Figure 5-13. Comparison of Transient *versus* Steady-State Heads.



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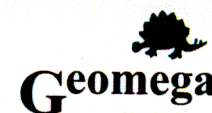
Figure 5-14.
Predicted Water Table Map, Layer 6, at 100 Years.

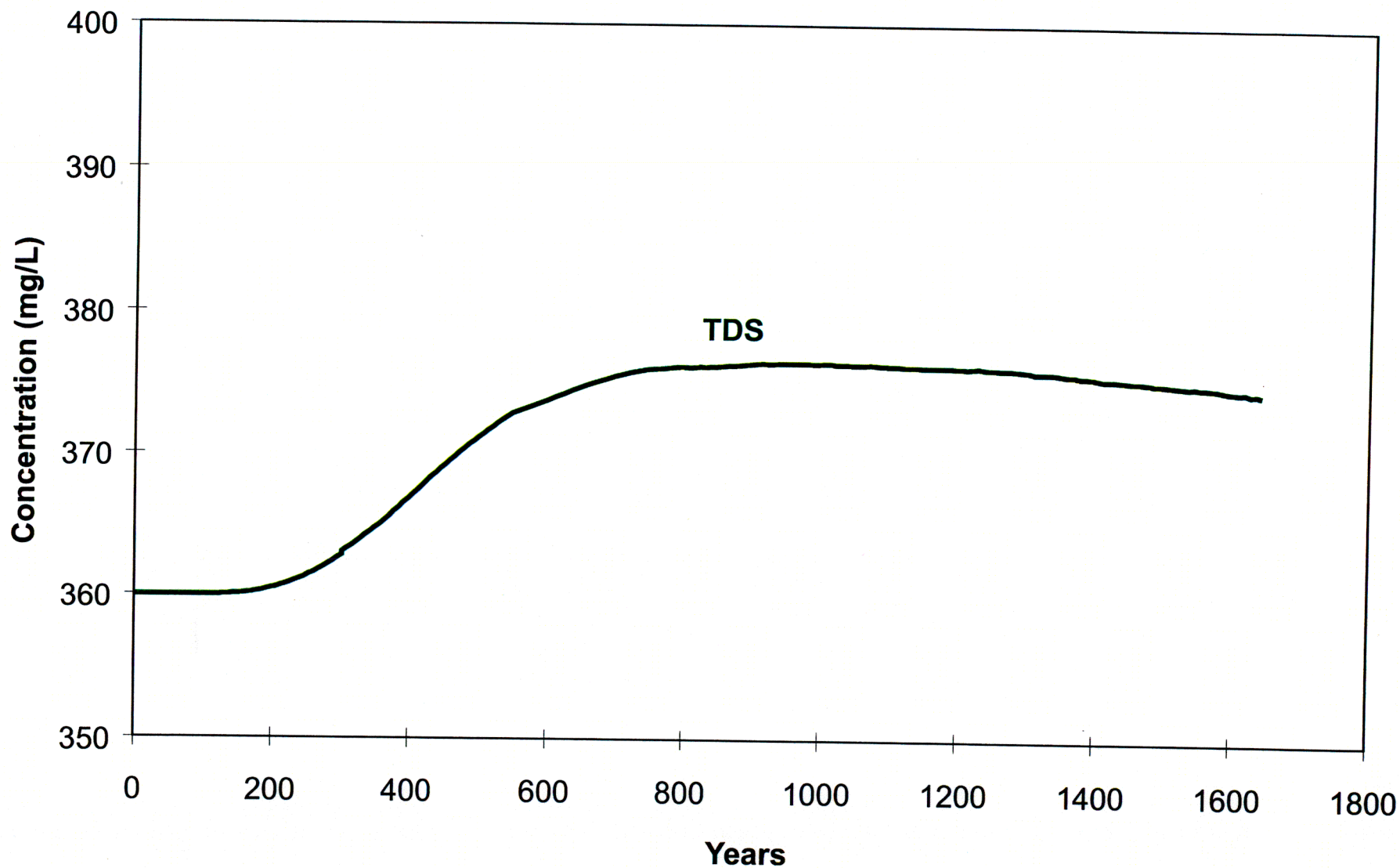




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Figure 6-1. Modeled Sulfate Concentrations *versus* Time
at WCC-G1 Assuming 3,040 mg/L TDS Source.

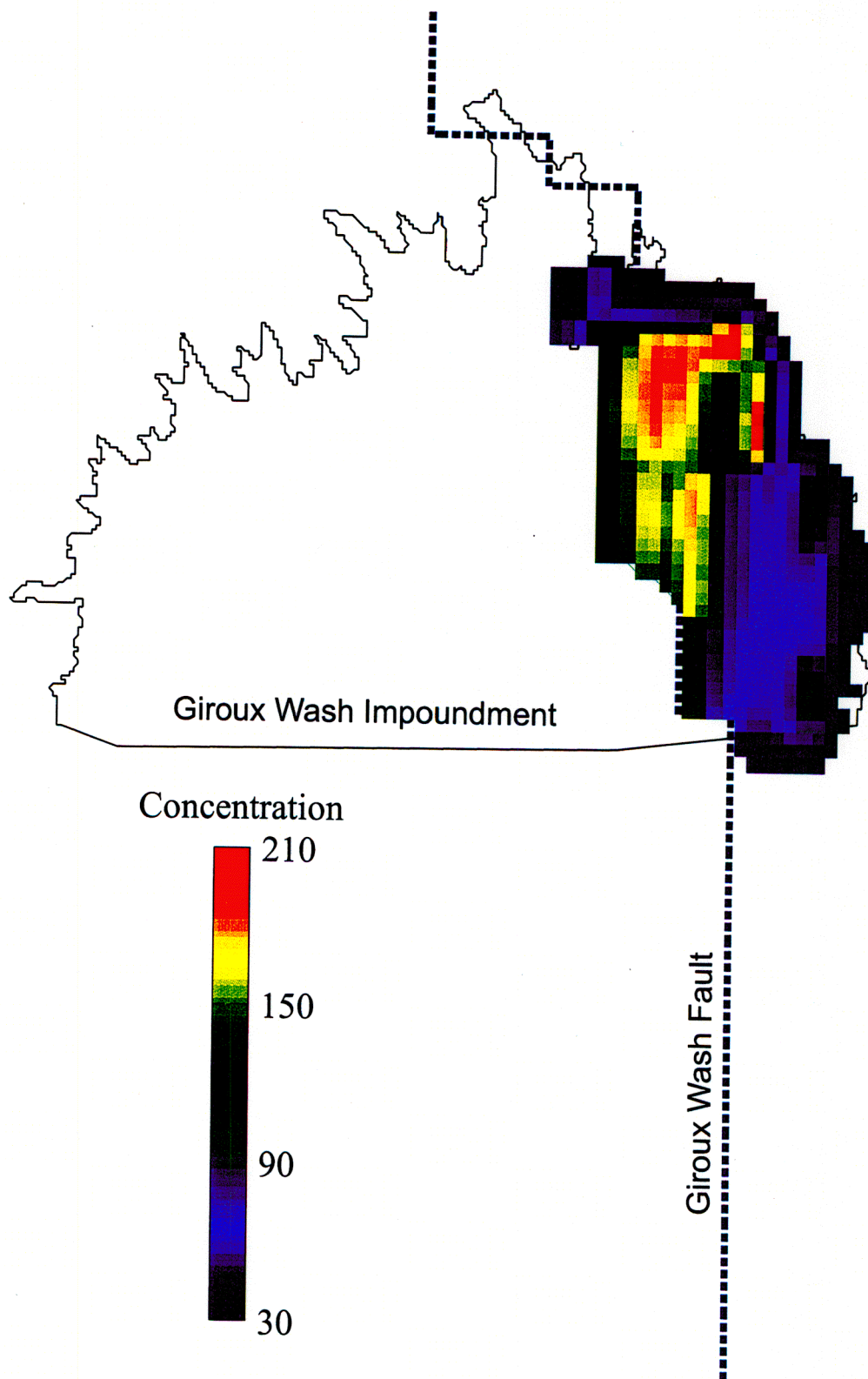




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Figure 6-2. Modeled TDS Concentrations *versus* Time
at WCC-G1 Assuming 3,040 mg/L TDS Source.

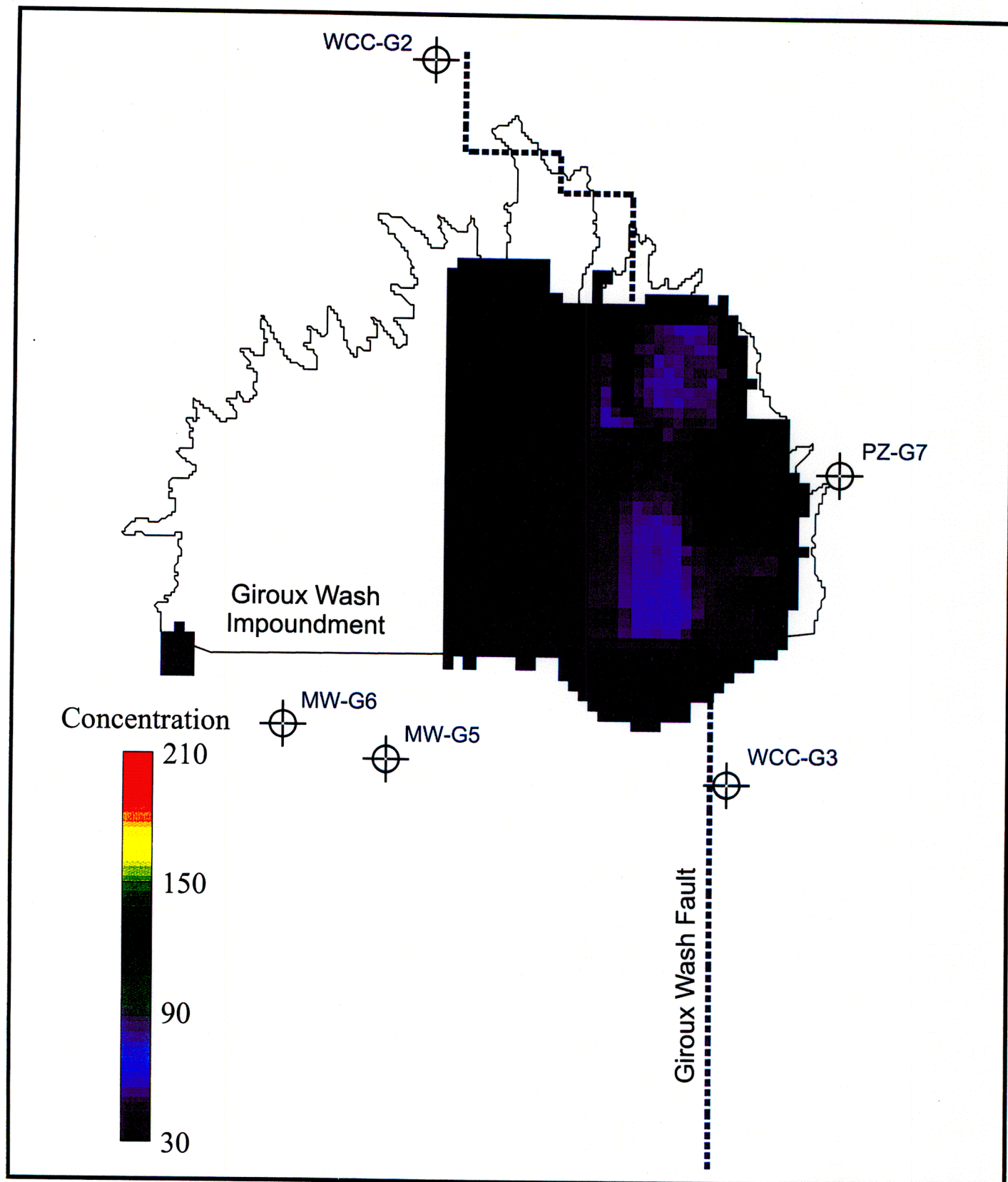




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Figure 6-3. Predicted Sulfate Isoconcentrations
in Layer 5 at 96 Years.

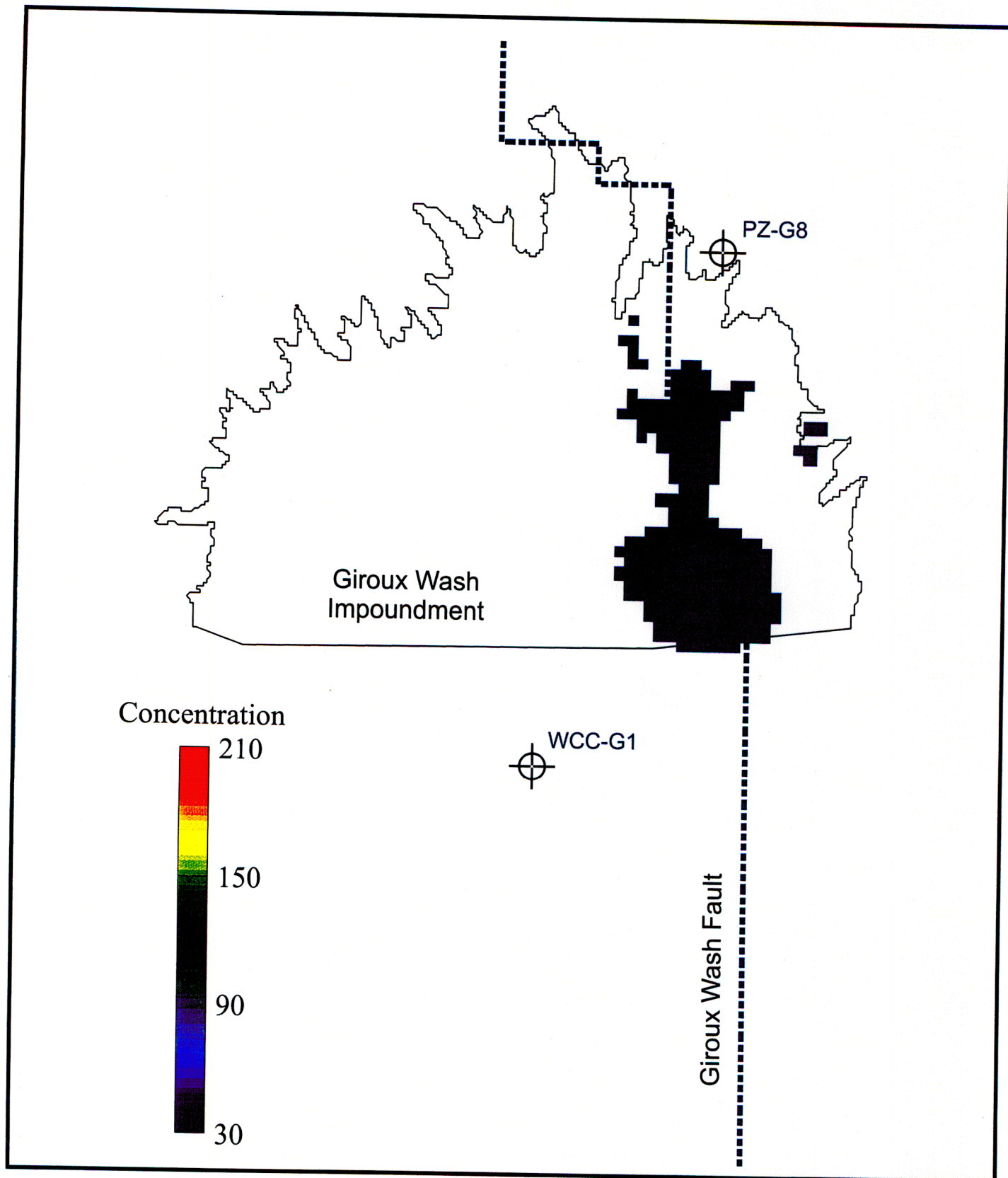

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Figure 6-4. Predicted Sulfate Isoconcentrations
in Layer 6 at 96 Years.

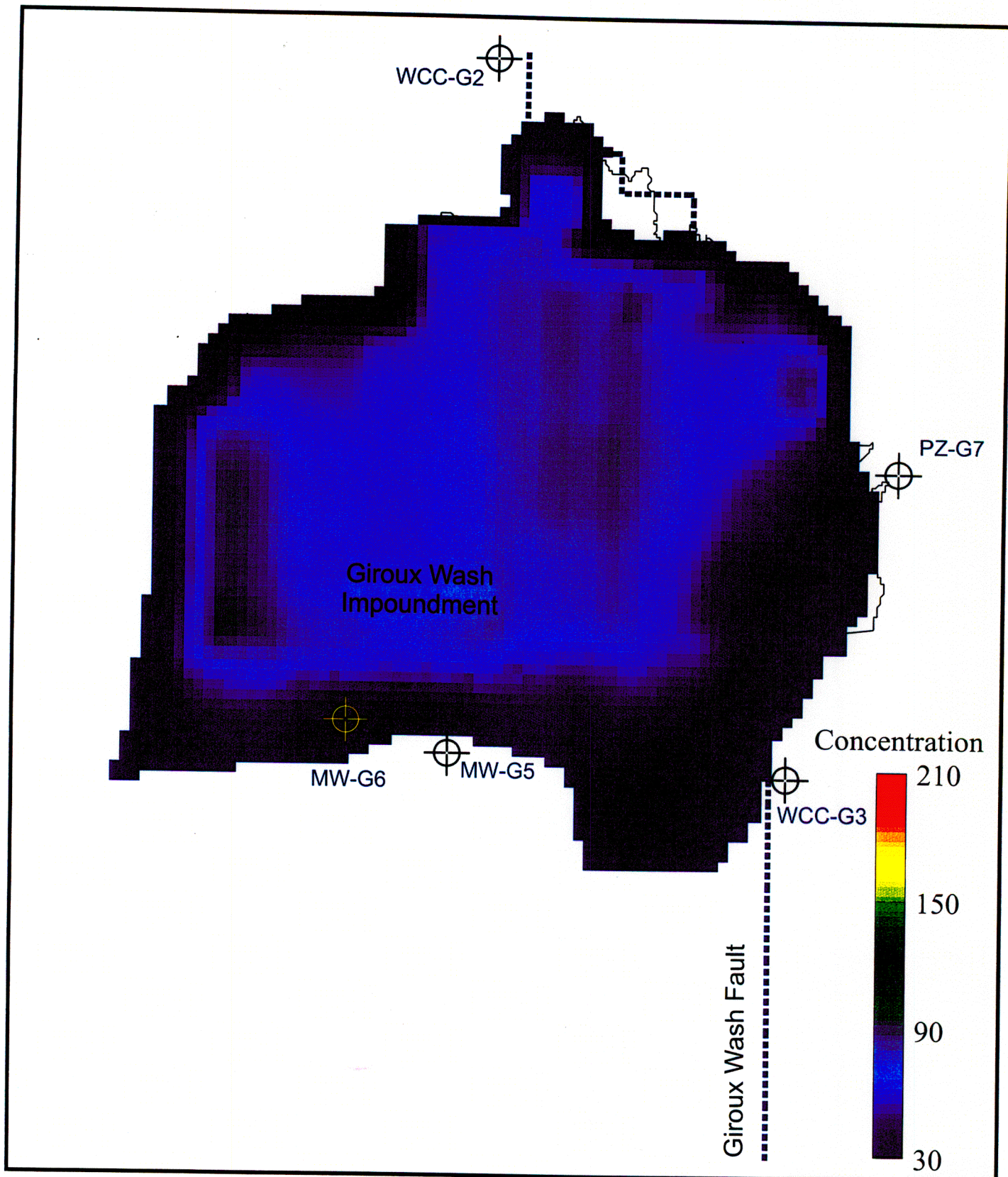

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Figure 6-5. Predicted Sulfate Isoconcentrations
in Layer 7 at 96 Years.

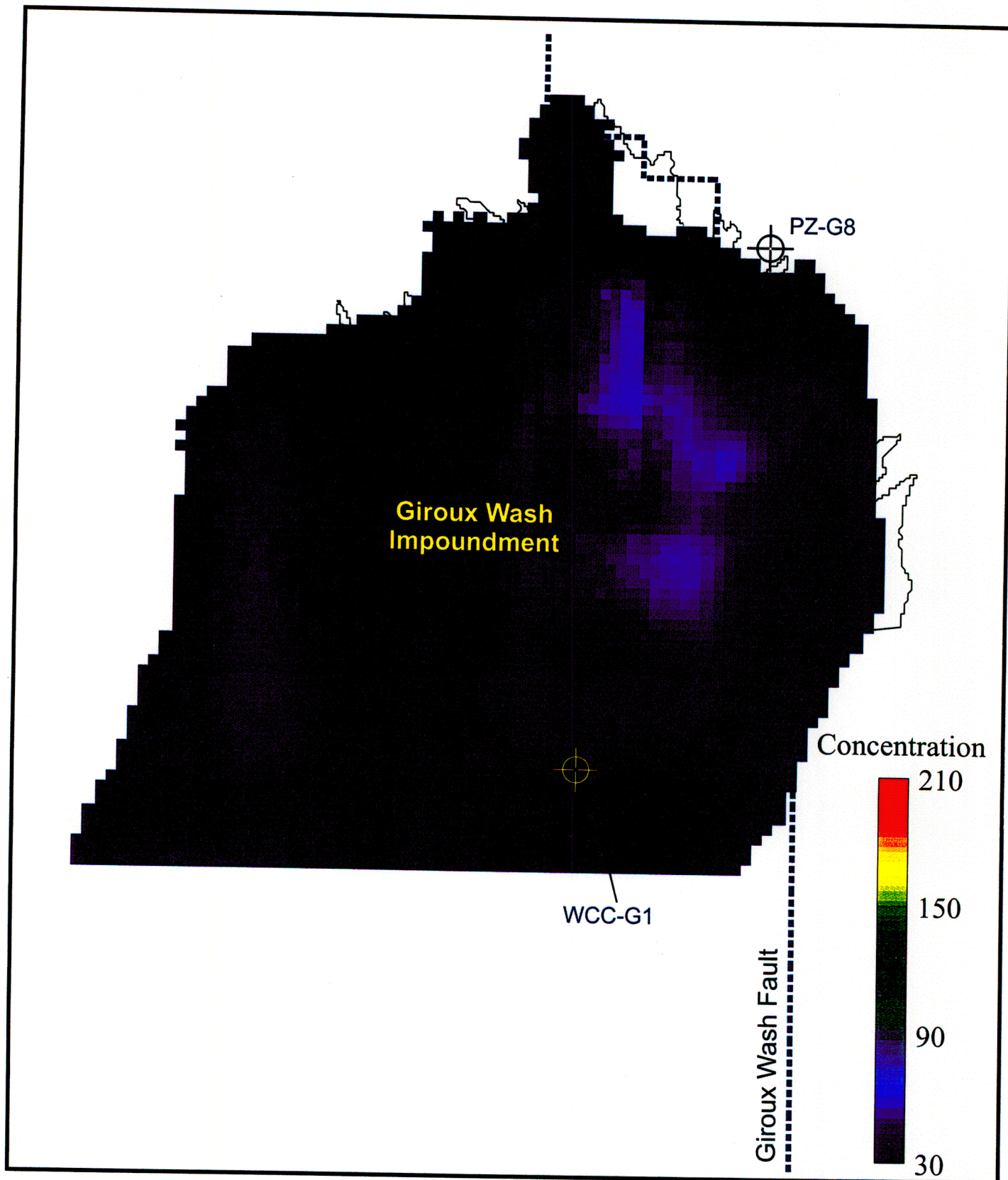

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Figure 6-6. Predicted Sulfate Isoconcentrations
in Layer 6 at 548 Years.

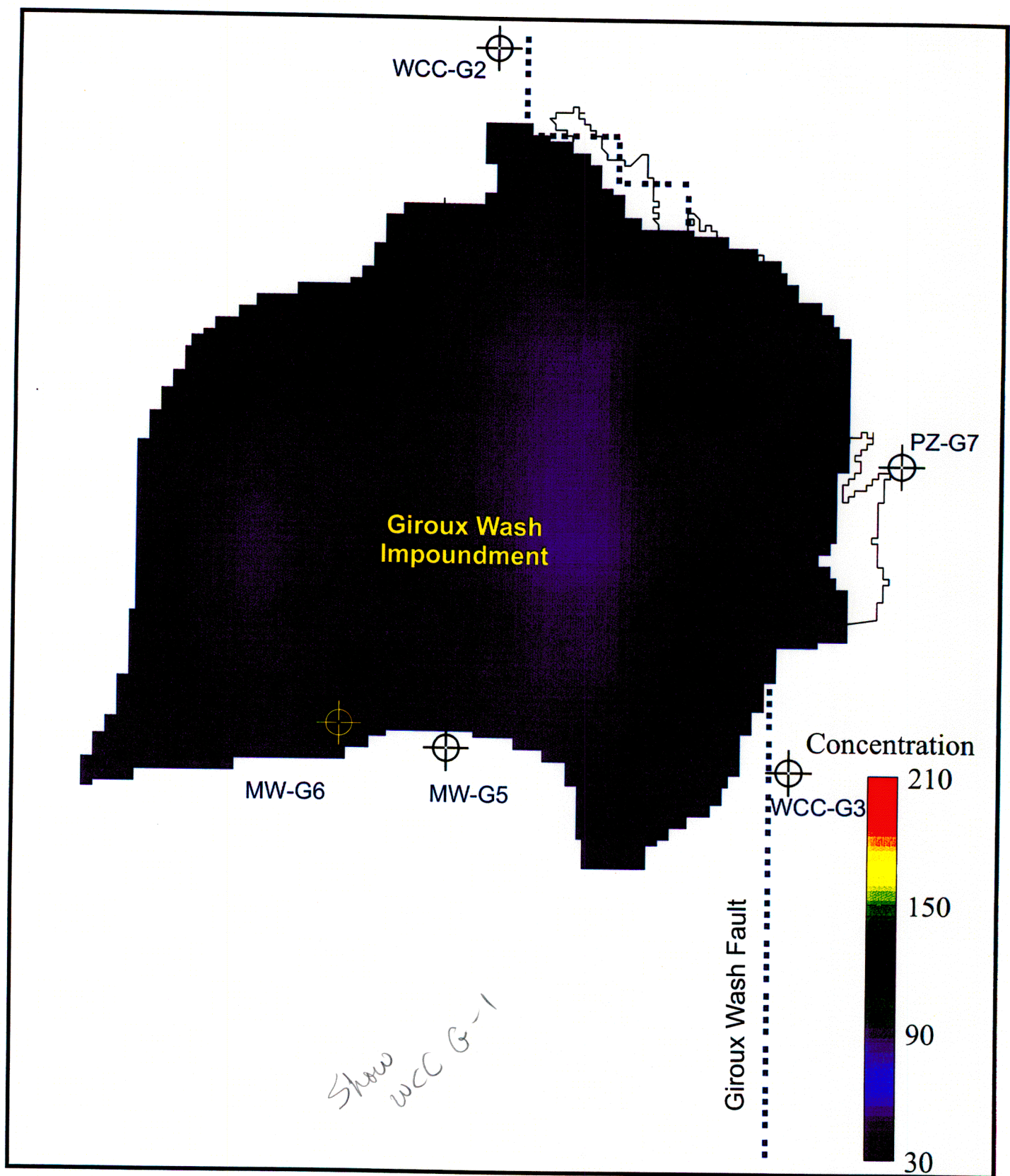

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Figure 6-7. Predicted Sulfate Isoconcentrations
in Layer 7 at 548 Years.

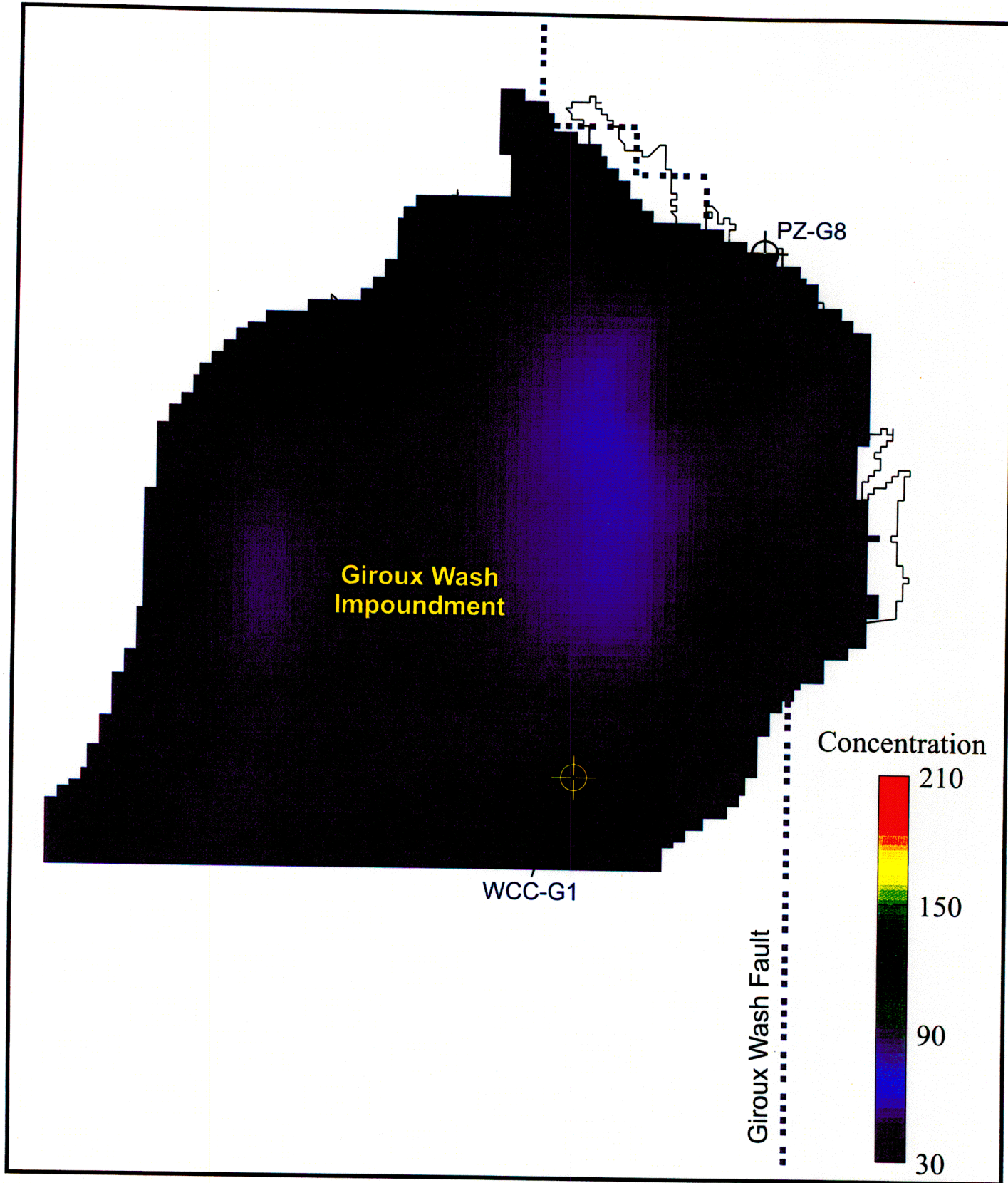

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Figure 6-8. Predicted Sulfate Isoconcentrations
in Layer 6 at 1644 Years.

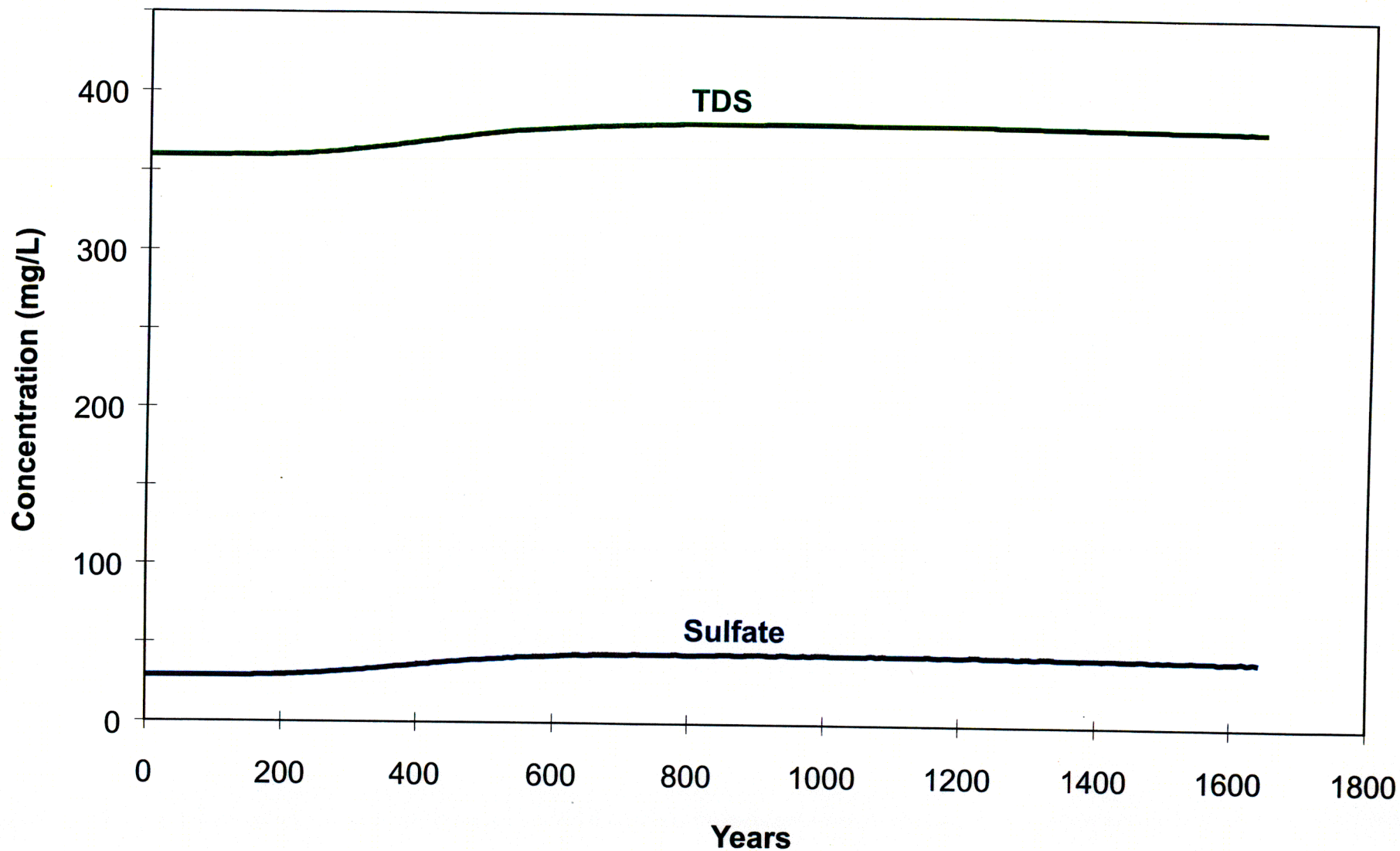




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Figure 6-9. Predicted Sulfate Isoconcentrations
in Layer 7 at 1644 Years.

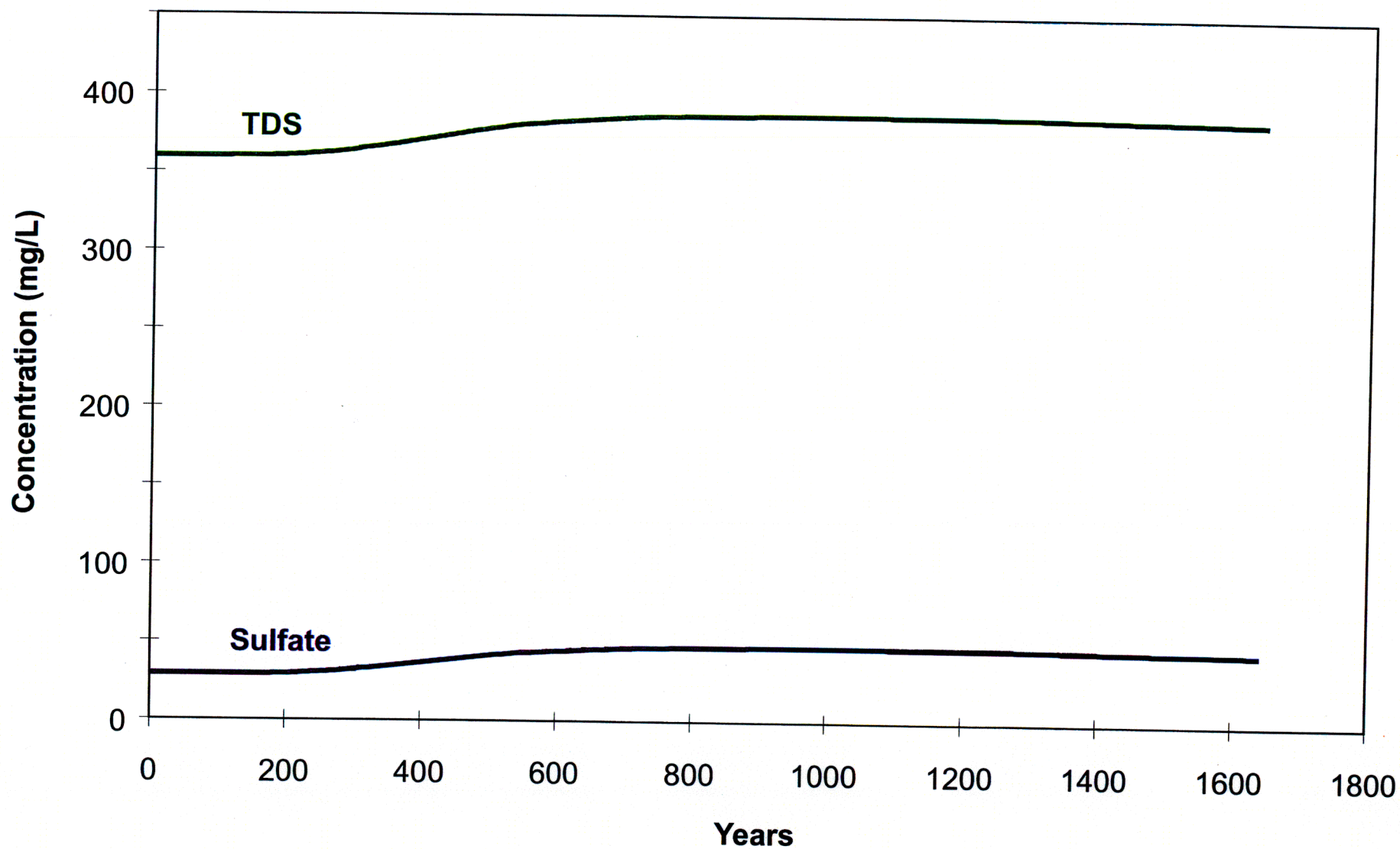

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Figure 6-10. Modeled Sulfate and TDS Concentrations *versus* Time
at WCC-G1 Assuming 4,000 mg/L TDS Source.





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Figure 6-11. Modeled Sulfate and TDS Concentrations *versus* Time
at WCC-G1 Assuming 5,000 mg/L TDS Source.

Appendix