APPENDIX 11-WW

NAVAJO MINE AREA IV GROUNDWATER MODELING REPORT

(Prepared by Norwest Corporation)

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NAVAJO MINE AREA IV.
GROUNDWATER MODELING REPORT

Submitted to:
BHP Navajo Coal Company,
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Norwest Corporation
950 So. Cherry St., Suite 800
Denver, Colorado 80246
Tel: (303) 782-0164
Fax: (303) 782-2560
Email denver@norwestcorp.com

www.norwestcorp.com

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1 INTRODUCTION

1.1 BACKGROUND

This report describes the numerical groundwater flow model developed for BHP Navajo Coal Company (BNCC) in support of a previously proposed different mining operation within resource area (Area) IV South of the BNCC coal lease, located on the western flank of the San Juan Structural Basin within the Navajo Nation Indian Reservation, southwest of Farmington, New Mexico. The groundwater flow model also included Area IV North within the model domain so that the affects of coal mining in Area IV North could also be simulated. Consequently, this model has been applied to simulate the affects of BNCC's proposed mining within Area IV North to meet its Pre-2016 fuel sales obligations with Four Corners Power Plant The model can also be applied to simulate the affects of future mining and reclamation within Area IV South and Area V as well as within the portions Area IV North beyond the Pre-2016 mine plan.

The coal seams to be mined include seams 2, 3, 4, 6, 7, and 8 of the Cretaceous age Fruitland Formation. Seams 7 and 8 extend over only a portion of the coal lease. The coal lease area and adjacent area within Area IV North is dominated by badlands and mesas with the Chaco River valley coursing from south to north approximately 1 mile west of the coal lease. The Chaco River flows north into the San Juan River approximately 18 miles north-north-west of the model area. The regional setting for the model area is shown in Figure 1-1. Although the Chaco River drains an area of more than 4,000 square miles, the flow in the river and in tributary drainages is ephemeral in the vicinity of the project site.

The BNCC coal lease at resource areas IV North and IV South is crossed by three arroyos, Cottonwood Arroyo at the north edge of Area IV North, Pinabete Arroyo through Area IV South and No Name Arroyo, which separates Area IV South from Area V. These arroyos flow into the Chaco River but are ephemeral streams that only flow in response to large storm events. Cottonwood Arroyo may experience temporary flows resulting from irrigation channel releases from the Navajo Indian Irrigation Project. Alluvial groundwater is present in the alluvium of both Pinabete and Cottonwood Arroyos, although the saturated thickness is variable and is often insufficient to yield water from the few dug water wells that have been installed for stock water use. Cottonwood Arroyo has a drainage area of approximately 80 square miles and flows from east to west along the north side of Area IV North. Pinabete Arroyo traverses in a northwest direction across Area IV South, and then flows west to the Chaco River. The drainage basin area of Pinabete Arroyo is approximately 60 square miles. The surface water drainage immediately south of Pinabete Arroyo is No Name Arroyo, which separates Area IV South from Area V. A topographic and structural high area exists on the west side of the Area V south of No Name Arroyo.

Groundwater recharge is quite low due to the arid climate. Evaporation rates are high, averaging over 60 inches per year, while precipitation is low, averaging less than 6 inches per year. Most precipitation occurs during several large high intensity precipitation events. Snow rarely accumulates in any significant depth over the site.

Groundwater modeling was performed to support the baseline hydrogeologic characterization and the probable hydrologic consequences (PHC) assessment of proposed mining and reclamation activities. The hydrogeologic units within the BNCC coal lease that could potentially be affected by proposed mining and reclamation include:

- The alluvium of Cottonwood and Pinabete Arroyos
- The Coal Seams of the Fruitland Formation
- The Pictured Cliffs Sandstone, located below the Fruitland Formation No. 2 Coal Seam

Among these units, only the alluvium of Cottonwood and Pinabete Arroyos supply water to wells located within or adjacent to BNCC's Navajo coal lease. The saturated thickness and yield of these alluvial wells is quite low but at times is sufficient to provide stock water via windmill driven pumps at dug wells. The water level in the alluvium varies with precipitation patterns. Alluvial groundwater levels are generally too low to supply water to dug wells in the Cottonwood alluvium west of the coal lease during most years and to dug wells in the Pinabete alluvium within the coal lease during dry years. For example, in the Fall of 2007 the saturated thickness of the Pinabete alluvium was less than 3-feet at monitoring well PA-2 located adjacent to dug well 13R-37. The groundwater quality in the Pinabete and Cottonwood alluvium is also poor with total dissolved solids (TDS), sulfate, fluoride, iron, and manganese concentrations above drinking water standards. Although the groundwater in the alluvium has been used for stock watering, the fluoride concentrations exceed the Navajo Nation Surface Water Quality Criteria for livestock use and sulfate and TDS concentrations exceed recommended criteria for livestock use (Appendix 6.G).

Although, groundwater is also found in the coal units of the Fruitland Formation and in the Pictured Cliffs Sandstone (PCS), which underlies the Fruitland Formation at BNCC coal lease, the yields from these units are quite low and wells are typically pumped dry during testing and well purging for sampling. The water quality in these units is also poor. The sulfate and fluoride concentrations at most monitoring locations exceed the Navajo Nation Water Quality Criteria for livestock use. Stone and others (1983) state that the Pictured Cliffs Sandstone cannot be considered a major aquifer, and it is important only because it is the water-bearing horizon immediately underlying the coals in the Fruitland Formation.

There are no water supply wells completed in the Fruitland Formation or the PCS within or near the project area. One well, 13-15-1, is located within Area V of BNCC's coal lease. The completion interval for this well is not known but is believed to be a PCS well based on the depth reported by Metric Corporation (1991). The well has not been used for at least 20 years and has been capped and welded shut.

Groundwater models are conceptual descriptions or approximations that describe physical systems using mathematical equations. Groundwater models used for a PHC assessment can range from simple empirical equations to complex numerical computer simulations of groundwater flow and groundwater chemistry. Regardless of the level of complexity, all groundwater models are based on certain simplifying assumptions which typically involve: the direction of flow, geometry of the hydrogeologic units, the heterogeneity or anisotropy of sediments or bedrock within these aquifer units, and the location of boundaries and conditions at these boundaries.

As a result of these assumptions and the uncertainties in the values of parameters and data required by the model, all models are an approximation and not an exact representation of the physical systems being modeled. In order to select and apply an appropriate modeling code it is necessary to:

- consider modeling objectives,
- have a thorough understanding of the physical system with sufficient site-specific data to apply the modeling code, and
- have sufficient data to assess how well the model approximates the groundwater conditions at the Site.

Extensive information on the baseline groundwater conditions at the Navajo Mine is provided in Chapter 6 Navajo Mine Permit Application Package (PAP). Information specific to Area IV North, Area IV South and Area V is provided in Appendix 6.G while regional groundwater information is also available from the U.S Geological Survey and the New Mexico Bureau of Mines and Mineral Resources Reports, and from the nearby San Juan Mine and CONSOL Energy's Burnham Mine, located outside of Burnham, New Mexico.

1.2 OBJECTIVES AND SCOPE

The first step in developing a groundwater model is to define the objectives of the study. The primary groundwater resource issue related to surface coal mining within Areas IV North and IV South concern the effects of proposed mining and reclamation on the quantity and quality of groundwater in the alluvium of Pinabete Arroyo, Cottonwood Arroyo and the Chaco River that provide potential livestock water supplies. Specific objectives of the groundwater model are as follows:

- The first objective is to provide a better understanding of the baseline groundwater flow systems within and adjacent to the proposed mining locations. Much of the model domain is under unsaturated and perched groundwater conditions, so it was determined that a full saturated/unsaturated flow model was needed to meet this objective.
- The second objective is to predict the transient groundwater changes that are expected during and after mining. In particular, these evaluations will assess the extent of drawdown in the Fruitland coals and the PCS and the approximate time frames for recovery to near steady state conditions following reclamation.
- The third objective is to estimate the expected level of saturation within the mine backfill and the groundwater flow paths and rates of flow from the mine backfill after recovery to near steady state conditions following mining.
- The fourth objective is to simulate transport of dissolved solids in the groundwater from the mine backfill in order to estimate the directions and magnitude of potential changes in groundwater concentrations that might occur and time-frames that might be involved in these changes.

The modeling process involved the following steps:

- development of a conceptual model of groundwater systems within the proposed mine area and adjacent area;
- selection of a numerical code or modeling software capable of representing the conceptual model;
- development of a three-dimensional groundwater flow model using the chosen software;
- calibration of the model such that it is representative of observed conditions; and
- application of the model to support the PHC assessment of proposed mining and reclamation.

This supporting document describes the model development, calibration and sensitivity evaluation, and discusses the application of the model for PHC assessment. Prior to developing the numerical groundwater flow model, it was first necessary to develop a conceptual model of the groundwater flow system. A conceptual groundwater model is a complex hypothesis of the characteristics and functions of a hydrogeologic system, including recharge and discharge relationships, groundwater flow within and between hydrogeologic units and the expected properties of these hydrogeologic units. Section 2 of this report presents the conceptual model, including the description of the model domain and basin hydrogeology. Section 3 describes the model code selection, model setup and application of the model code to the conceptual model. Section 4 describes the model calibration, the steady state baseline simulation results, and the sensitivity evaluations. Section 5 describes the application of the model to simulate the results for a specific mine plan. The mine plan discussed in this section is BNCC's mine plan revision submitted to OSM on February 15, 2011. The revision provides the plans to conduct surface coal mining and reclamation activities within a 704 acre mining block in Area IV North to allow mining to continue through mid-2016 in order to meet mine lease terms with the Navajo Nation and contractual coal tonnage delivery obligations with the Four Corners Power Plant. The results of the simulations described in Section 5 are included in the PHC in Chapter 11 of BNCC's mine permit revision submitted to OSM on February 15, 2011. The calibrated model also provides a tool that can be used for subsequent permit revisions. The modeling results for subsequent mine plan revisions will be provided in the PHC revisions in Chapter 11 of the Navajo Mine Permit Application. References can be found in Section 6 of this report.

2 CONCEPTUAL MODEL

A conceptual model of the groundwater flow system is the foundation on which the numerical model is based. The conceptual model needs to incorporate the major processes and factors controlling the magnitude, rate, and direction of groundwater flow. The groundwater flow systems at a particular site are governed by geology, topography, and groundwater recharge. This section summarizes the conceptual model of the groundwater flow system at the project location. The nature and patterns of groundwater flow, from the locations where water enters the subsurface at a recharge area, to the locations where groundwater discharges, from a groundwater flow system. A combination of groundwater flow systems from local to regional in scale can develop in an area (Toth, 1963). Intermediate and regional systems tend to predominate in arid areas and areas with gentle topography. Local flow systems tend to be dominant in areas with high topographic relief and wetter climates.

Groundwater flow models are used to calculate or simulate the rate and direction of movement of groundwater through geologic units. The simulation of groundwater flow requires a thorough understanding of the hydrogeologic characteristics of the site, including:

- the extent, thickness and characteristics of hydrogeologic units included in the model domain;
- the boundary conditions for the model domain;
- the distribution and magnitude of either groundwater recharge or groundwater discharge, which is needed to characterize the overall water balance of the groundwater flow system; and
- the horizontal and vertical distribution of hydraulic heads throughout the modeled domain, which is needed for model calibration.

2.1 HYDROGEOLOGIC UNITS

The San Juan Basin is a typical asymmetrical, Rocky Mountain basin, with a gently dipping southern flank and a steeply dipping northern flank (Stone et al., 1983). The project site is located along the western flank of the central basin with a northwest trending axis parallel to the Hogback monocline located northwest of the project site. The stratigraphic section in the project area reflects the Late Cretaceous transition of a shallow marine depositional environment to a terrestrial fluvial depositional environment. The four formations encompassing this depositional environment change are (in ascending order): the Lewis Shale, the Pictured Cliffs Sandstone, the Fruitland Formation, and the Kirtland Shale.

The Lewis Shale contains the last purely marine shales deposited in the Upper Cretaceous. It consists of gray to black shale with some interbeds of sandy limestone, brown sandstone, and bentonite. The Pictured Cliffs Sandstone (PCS) conformably overlies and intertongues with the Lewis Shale. This formation consists of both delta-front and barrier-beach sediments and marks the change to a littoral (near-shore) depositional environment. The upper two-thirds of the PCS consists of a generally coarsening upward sequence of light gray, fine to medium grained sandstone while the lower one-third of the formation consists of interbedded shale and sandstone. The total thickness of the PCS is approximately 110 to 120 feet in the model area.

The Fruitland Formation, which conformably overlies the PCS, contains minable coal seams that are the target for proposed surface mining. The coal seams are highly continuous within the coal lease area and are nearly flat lying, with a dip of up to 2 degrees to the east-northeast. Localized pinches, rolls, and occasional faults with minor offsets are encountered. The topography within the project area rises gently from west to east, with the overburden becoming thicker from west to east. The coal seams outcrop or subcrop close to the western limits of the mine lease. The coal resource is burned or washed out beyond the western limit of the mine lease and within portions of the mine lease for some of the upper coal seams. The upper seams typically do not exist within much of the lower topographic surface in the western portions of the coal lease, but come into the sequence on the eastern portion of the lease area where the topography rises and as the strata dip to the east.

Surface soils are thin or nonexistent, and the near surface geology is typically comprised of a layer of weathered shale and sandstone along with unconsolidated eolian sands. Deposits of Quaternary alluvial sediments and unconsolidated eolian sands also occur along the ephemeral stream channels. The unconsolidated surficial materials overlie a competent overburden comprised of shales, sandstones, and siltstones. Within the project area the stratigraphically highest coal seam (Seam 8) occasionally lies directly under the unconsolidated layer. Portions of Seams 8 and 7 within the lease are weathered, and very little of Seam 8 is found within Area V. Overburden depths range from a few feet to over 80 feet. Interburdens and partings are generally composed primarily of soft gray shale, a dark gray siltstone, and carbonaceous shale. Sandstone lenses and stringers with minor thickness are found to a limited extent within the interburden, but shales and siltstones are predominant.

The Kirtland Shale conformably overlies the Fruitland Formation to the east of the coal lease. This formation is divided into two units, the upper shale member, which includes the Farmington Sandstone Member, and the lower shale member. The lower shale member is composed of gray claystone shales that contain a few thin interbeds of siltstone and sandstone. No coal beds exist in the Kirtland Shale (Fasset and Hinds, 1971).

A more thorough description of the regional and local geology of the Navajo Mine SMCRA permit area is provided in Chapter 6 of the Navajo Mine PAP, with specific information concerning Areas IV North, IV South and V in Appendix 6.G. Based on both regional and site-specific information, the Fruitland Formation and associated coal units and the PCS are unsaturated, or partially saturated, near the outcrop of these units on the west side of Areas IV North, IV South and V of the coal lease, but become saturated to the east and down dip of the outcrop.

One conceptualization of the hydrogeology of the model area is to consider the Fruitland Formation as a single hydrogeologic unit. The single hydrogeologic unit approach was previously proposed by Billings and Associates (1987) for modeling groundwater at the Navajo Mine because of the complexity of the individual coal seams, which often split or pinch out. Kaiser et al (1994) note that “Regionally, the Fruitland Formation is a single hydrologic unit, but compartmentalization is indicated locally by large vertical and lateral pressure gradients.” On the more localized scale of Area IV of BNCC’s Navajo coal lease, the interbedded strata and coal beds have a significant influence on the hydrogeology of the Fruitland Formation. Although the hydraulic conductivities of the coals are relatively low, they are still considerably higher than those of the interbedded shales, resulting in large vertical potentiometric gradients among the coals within the coal lease. One of the primary hydrogeologic changes to occur as a result of mining is the removal of the coals and the interbedded shales and sandstone strata in the overburden and interburden resulting in more homogeneous and isotropic conditions within the mine backfill. Furthermore, water chemistry has been found to vary among the individual coal units within the Fruitland Formation. Typically, TDS concentrations increase with depth, while sulfate concentrations decrease with depth.

Although the coal geology is complex with multiple coal bed splits and coal beds that pinch out, there is good correlation and spatial continuity for particular coal zones, or seams, within BNCC’s Navajo coal lease. These coal seams may feature one coal bed, or they may include splits with multiple coal beds. Within the Navajo coal lease these coal zones, or seams, are numbered sequentially from the bottom coal zone (No. 2) to the uppermost coal in this area, the No 8 coal. The No. 1 coal zone and the No. 5 coal zone are not present within BNCC’s Navajo coal lease, while the No. 2, No. 3, No. 4, No. 6, No. 7 and No. 8 coal zones all occur within Areas IV North, IV South and V. For these reasons, the conceptual hydrogeologic model and the numerical groundwater model for the project handles the individual coal zones, or seams, as separate and distinct hydrogeologic units.

The PCS, the first hydrogeologic unit below the Fruitland Formation has been included in the groundwater flow model. The top of the Lewis Shale has been included as the base of the model domain. Generally, a shale zone such as the Lewis Shale would be considered as an impermeable boundary. However, given the low recharge rates at the site, overall low permeability of the Fruitland Formation shales and coals, and the relatively low permeability of the PCS, the flow conditions at the boundary between the PCS and Lewis Shale were found to be significant for calibrating the groundwater flow model.

The delineation of the hydrogeologic units within the model domain was developed from the extensive geologic and groundwater information developed for BNCC's Navajo coal lease. The extent of geologic and groundwater information that is available to support the conceptual and numerical model is more limited beyond the coal lease boundaries. Consequently, information was obtained from a variety of sources to help delineate the hydrogeologic units and define groundwater conditions for the portions of the model domain that are beyond the limits of the coal lease. Information sources included various regional geologic and hydrogeologic reports sited in the references provided at the end of this report, the hydrogeologic data in the Navajo Mine and Burnham Mine Permit Application Packages, and logs from oil and gas wells located within or near the model domain.

2.1.1 Hydraulic Conductivities of Modeled Units

Another element of the conceptual model is to define to the extent possible the properties of these hydrogeolgic units, including hydraulic conductivities and storage characteristics of these hydrogeologic units. The representative range for hydraulic conductivities of individual model layers is provided in Table 2-1. The sources of information used to establish the range of hydraulic conductivities and storage characteristics of modeled hydrogeologic units is provided in Attachment 1. Hydraulic conductivities for the hydrogeologic units were modified during model calibration. Calibrated hydraulic conductivity values are shown in Table 2-1 along with the representative range of values determined from local or regional data.

2.1.2 Storage Coefficient and Specific Yield of Modeled Units

The amount of water an aquifer can yield is described by the storage parameters: specific storage and specific yield. The specific storage of a confined aquifer is the volume of water that a unit volume of the aquifer releases from storage per unit decline in head. Specific storage is a measure of the compressibility of the aquifer matrix and the expansion of water. In unconfined aquifers, changes in storage are controlled by the specific yield and not by the compressibility of the matrix or the water in storage. The specific yield is the volume of water that drains from an unconfined aquifer per unit decline in head. The specific yield is less than the porosity but much larger than specific storage.

Specific storage values for the various hydrogeologic units were obtained from aquifer testing results and from literature values for similar formations in other Rocky Mountain sedimentary basins. The specific storage value was set to 3.8×10^{-6} ft^{-1} in the PCS based on the observation well response during a pumping test at PCS well T4-1 (Attachment 1). This specific storage estimate for the PSC is consistent with the specific storage reported by Lohman (1972, p 53) as a reliable estimate for confined sedimentary bedrock aquifers. Specific storage values were also set to the PCS value of 3.8×10^{-6} ft^{-1} for the Fruitland Formation overburden and interburden layers. This value is within the range of 2×10^{-5} and 1×10^{-6} listed by Bredehoeft et al (1983) for specific storage values determined from laboratory consolidation tests of Cretaceous shale confining layers. Also, it is expected that the specific storage for the sedimentary rock in the Fruitland Formation should be similar to the specific storage values found in the underlying PSC and in the literature for confined sedimentary bedrock aquifers. Specific storage for the coal units was set to 2.8×10^{-5} ft^{-1}. The specific storage for the coal was estimated from observation well response during a pumping test of the No. 8 coal seam well at the San Juan Mine (Attachment 1).

Specific yield (under unconfined conditions) was assumed to be similar to estimated effective porosities. Specific yield will always be lower than porosity as some of the groundwater will not drain from the formation since it is held by capillary forces. A specific yield of 20 % was used for the alluvium and overburden and interburden units in the model. A lower specific yield of 0.5 % is used for the coals due to the low effective porosity of the coals (Attachment 1).

2.1.3 Unsaturated Parameters of Modeled Units

Little hard data was available on unsaturated zone parameters in the area of the model domain. It was assumed that high capillary head wetting curves were needed given the arid site climate in the study area.

2.2 MODEL DOMAIN AND BOUNDARY CONDITIONS

An essential part of both the conceptual and numerical models is the representation of the horizontal and vertical boundaries of the hydrogeologic system (the model domain) and the delineation of the hydrogeologic units within the model domain. It is also essential that the hydraulic head or flow conditions be defined for each of the hydrogeologic units along the boundaries of the model domain.

The vertical extent of the hydrogeologic model is from the ground surface to the base of the PCS. A head dependent boundary condition was established through model calibration to represent the Lewis Shale at the base of the PCS.

The horizontal extent of the hydrogeologic model is provided in Figure 1-1. The model domain was established where there are physical boundaries, such as the outcrop of the geologic units west of the project as shown in Figure 1-1. The model domain extended sufficient distances to the east and south of the coal lease where the required assumptions about hydrogeologic conditions at these boundaries are expected to have limited influence on the predicted changes in the groundwater system due to drawdown associated with proposed mine pit advance and recovery following planned backfill sequences as evidenced by minimal drawdown and minimal changes in fluxes at these boundaries. The model domain extended to just north of the Cottonwood Arroyo, near where there are a number of wells to better define the steady state pre-mine conditions at the north boundary.

The boundary conditions at the horizontal model extents were established based on the conceptual model. The outcrop of both the PCS and the Lewis Shale is shown in Figure 1-1 along with the model extents. A no flow boundary condition was designated for the west boundary of the model domain along the outcrop of the PCS/Lewis Shale stratigraphic interface. Since this model is an unsaturated-saturated flow model, saturation to the west extends as far as the model solution determines for the calibrated steady-state pre-mine condition but no further than the physical outcrop boundary.

The boundary conditions for the PCS on the south, east and north boundaries of the model domain were established based on the conceptual model and the potentiometric surface. The potentiometric surface within the model domain is well characterized from current and historic water level monitoring data from wells completed in the PCS within the vicinity of BNCC’s Navajo coal lease and from Burnham Mine monitoring wells to the south of the Navajo coal lease. In addition, the PCS outcrop map in the vicinity indicates a large outcrop area for potential recharge along the Hunter Wash valley south of the model domain as shown in Figure 1-1. It is expected that potentiometric elevations for the PCS along Hunter Wash are close to the elevation of the channel bottom. Down dip to the northeast and along the east side of the model domain, the potentiometric gradient is believed to be from south to north as indicated by Kaiser et al (1994). Localized discharge is expected to occur along the topographic lows where the PCS subcrops beneath the alluvium of the ephemeral streams. The regional potentiometric surface depicted in Figure 1-1 was developed based on all these sources of information.

A constant head boundary has been defined for the PCS based on the potentiometric surface along the north, south and east boundaries. A no flow boundary has been specified along the west boundary. Boundary conditions for the model layers corresponding to the Fruitland Formation Coal Seams were established along portions of the south boundary where the PCS potentiometric surface is above the base of the coal layer. Constant head boundary conditions were defined at these locations along the south boundary based on the potentiometric surface of the PCS. Constant flux boundary conditions were established for the coal layers along the north model boundary east of the location where a portion of the south end of Dixon Pit of the Area III mine crosses the boundary. The fluxes for boundary conditions were determined based on the potentiometric gradient of the PCS, and the transmissivities of the coals at these locations. No flow boundary conditions were established for the Fruitland Formation layers long the west and east boundaries and along the north model boundary west of the location where a portion of the south end of Dixon Pit of the Area III mine crosses the boundary. The no flow condition for the Fruitland Formation along this segment of the north boundary represents the conceptual model depiction of the lower Cottonwood valley as a local discharge area with no flow to the north. The no flow condition for the Fruitland Formation along this segment of the east boundary represents the conceptual model depiction of the general northerly direction of flow in the Fruitland Formation along this boundary. Based on the transient simulations for the Area IV North mine plan, the northern boundary conditions appear to have minimal influence on the predicted changes in the groundwater system due to mining and backfilling.

A constrained constant head boundary was also established where the alluvium of Brimhall Wash, No Name Arroyo, Pinabete Arroyo and Cottonwood Arroyo occur along the western boundary of the model domain. A constrained constant head boundary was also extended into the model layer representing the PCS below the alluvium. The constraint on the boundary was that there could be no inflow to the model domain at the constant head boundary. The constant head was determined based on average depth to alluvial groundwater near the mouth of these ephemeral streams. Constrained head dependent boundary conditions analogous to drain boundaries were also established along the lower portions of model layer representing the alluvium along Cottonwood Arroyo, Pinabete Arroyo, No Name Arroyo and Brimhall Wash.

2.3 DISTRIBUTION AND MAGNITUDE OF GROUNDWATER RECHARGE

The conceptual model also includes an interpretation of spatial relationships between recharge and discharge and the approximate rates of recharge and discharge, including the groundwater inflows and outflows from the model domain. A critical aspect of hydrogeologic modeling is obtaining a reliable estimate of the magnitude of either groundwater recharge or groundwater discharge in order to constrain the overall water balance.

In hydrogeologic settings where groundwater discharge is primarily at streams, an estimate of discharge can generally be determined from measurement of the baseflow of the streams. However, this method for measuring discharge cannot be applied in arid environments, where groundwater discharge rates are low and insufficient to support baseflow at any time. Recharge rates are quite low at the site due to the arid climate. Annual precipitation averages about six inches (150 mm) per year with most precipitation occurring during several large high intensity precipitation events during the seasonal ‘monsoon’ periods. These generally occur in March and August of each year. Snow rarely accumulates in any significant depth over the project area.

Summers are hot with low relative humidity. Evaporation rates are high, averaging over 60 inches per year.

Fortunately, reliable estimates of groundwater recharge rates at the Navajo Mine were obtained from studies conducted by Stone (1984, 1986, and 1987). Recharge estimates for undisturbed areas at the Navajo Mine ranged from 0.002 to 0.09 in/yr and are expected to be higher at surface depressions and impoundments.

“Badlands” topography comprises about half of the drainage basins of Cottonwood Arroyo, Pinabete Arroyo and No Name Arroyo and accounts for the high discharge and flow intensities observed in these ephemeral streams. Little groundwater recharge occurs within the badlands areas, due not only to the low rainfall rates, but also to the high proportion of rainfall that results in runoff. The low permeability of sodic clay soils nearly precludes groundwater recharge within badlands areas.

Groundwater recharge from precipitation and ephemeral stream flow within the project area moves vertically downward through the interbedded shales and coal units of the Fruitland Formation and into the PCS. Where Fruitland Formation coals are saturated, groundwater will flow laterally. Based on information obtained from water levels measured in the coal seam wells and piezometers, the flow directions in the coals within the model domain are toward the north-northeast.

Although the vertical hydraulic conductivities of the interbedded shales in the Fruitland Formation are quite low, recharge rates are lower still. Direct recharge rates measured by chloride mass balance methods on undisturbed areas at the Navajo Mine ranged from 0.002 to 0.09 in/yr, (Stone 1987). The highest recharge rate of 0.09 in/yr was for valley terraces while the lowest recharge rate of 0.002 in/year was for badland areas. Recharge from upland flats averaged 0.03 in/year.

Based on the research by Kearns and Hendricks (1998), aerial recharge is thought to occur during very large precipitation events and during extended wet periods with increasing soil moisture. Recharge is expected to be higher along ephemeral stream channels with saturated alluvium and surface impoundments. Although Stone’s research (Stone, 1986 and 1987) did not include recharge estimates for ephemeral stream channels and surface impoundments, he does provide an estimate of an average recharge rate of 0.16 inches per year from depressions within reclaimed mine areas at the Navajo Mine.

Slopes were calculated based on the U.S. Geological Survey (USGS) digital elevation model (DEM) and Stone’s recharge rate estimates for geomorphologic categories were then assigned to various slope ranges in order to estimate spatially varying recharge rates for the groundwater model. These categories, slope ranges, the associated recharge rates from Stone's research, and the associated model recharge rates are provided in Table 2-2.

2.4 POTENTIOMETRIC LEVELS AND GROUNDWATER FLOW

A potentiometric surface map for the PCS within the model domain is provided in Figure 1-1. As indicated on the potentiometric surface map, groundwater flow is from the recharge areas at the outcrops along Hunter Wash in the south toward the regional discharge area to the north and locally toward topographic lows in the stream valleys along the west side of the model domain. Potentiometric data for the No 2, No. 3 and No. 8 coal seams indicate a general potentiometric gradient to the north northeast, although the data are limited and are not sufficient to identify possible local gradients toward topographic lows and drainages.

3 GROUNDWATER MODEL SETUP

The low rate of recharge and the interbedded strata at the site results in large vertical downward potentiometric gradients with perched groundwater zones. One of the primary hydrogeologic changes to occur as a result of mining is the removal of the coal and the interbedded shales and sandstone strata and placement of a more homogeneous post mine backfill. Saturated groundwater flow models, such as MODFLOW, are incapable of handling three-dimensional unconfined situations with several dry model layers separating a water table from perched groundwater overlying low conductivity units. Consequently, in order to meet the modeling objectives, a multi-layer numerical groundwater flow model of the project area was developed using the FEFLOW (Finite Element subsurface FLOW system) software developed and supported by DHI-WASY GmbH, a German research and consulting group specializing in groundwater and surface water hydrology. The software uses a finite element analysis technique to solve the groundwater flow equations for both saturated and unsaturated conditions.

FEFLOW can be efficiently used to describe the spatial and temporal distribution of groundwater quality constituents, to estimate the duration and travel times of these constituents in aquifers and to assist in designing alternatives and effective monitoring schemes. It includes a sophisticated interface with GIS applications such as ArcInfo, ArcView and ArcGIS for ASCII and binary vector and grid formats. FEFLOW is used worldwide as a high-end groundwater modeling tool at universities, research institutions, government agencies and engineering companies.

Although the objective of the groundwater modeling study is to model flow and transport in the saturated zone, given the arid climate and the perched groundwater conditions over much of the study area, a full saturated/unsaturated implementation of FEFLOW was used in modeling.

3.1 MODEL MESH DISCRETIZATION

The model domain was discretized on a triangular mesh pattern as shown in Figure 3-1 to establish a 3D finite element mesh of 6-node triangular prisms. The groundwater flow model domain was established as described in Section 2.2. The element size was chosen to be sufficiently small to capture significant variations in topography, hydrology, and geology but large enough to minimize the model size. The pre- and post- mining steady state model mesh includes additional detail within the coal lease area and the areas of Cottonwood, Pinabete No Name Arroyos and Brimhall Wash. The pre- and post-mining steady state model mesh contains 805,280 elements and 424,821 nodes. The post-mining transient model contains 855,176 elements and 450,660 nodes.

3.2 MODEL LAYERS

The model is discretized vertically into 29 slices corresponding to 28 layers to accommodate the hydrogeologic units of interest. Layers are continuous horizontally across the model. Hydraulic parameters were assigned to each hydrostratigraphic unit through the corresponding model layer. Additional layers are needed in the finite element formulation to accommodate the transition between hydrogeologic units and for the implementation of boundary conditions in the coal layers. Thin (1.0 ft thick) buffer layers were added to reduce the conductivity contrast between the low conductivity overburden and interburden layers and the higher conductivity coals to improve model convergence. These buffer layers were assigned hydraulic properties of the corresponding overburden, or interburden, unit. Table 3-1 summarizes the correlation between model layers and slices and hydrostratigraphic units used in model design.

Implementation of the conceptual hydrogeologic model into the numerical groundwater model for the project includes the individual coal zones or seams as separate and distinct hydrogeologic units. Spatial grids with the elevations of the top of the PCS and the top and bottom of all coal beds within and adjacent to the coal lease were provided by BNCC. Additional data from the Burnham Mine, and surface topography of the PCS outcrop were used to extend the top of the PCS beyond the coal lease area. The individual coal beds were also identified according to coal zone. These data were used to construct the model layers. Additional data from Burnham Mine was used to extend the coal layers to the south. The top and bottom of the individual coal zones were determined from the upper and lower coal bed within the particular seam at individual grid locations. The Lewis Shale is a low conductivity unit that forms the base of the modeled groundwater flow system and was included as a head dependent boundary in the model. The top of the Lewis Shale was assumed to be 120 feet below the top of the PCS. The top surface of the model is based on topography derived from USGS DEMs.

3.3 MODEL BOUNDARY CONDITIONS

The conceptual boundaries discussed in Section 2.2 are implemented in FEFLOW as no flow boundaries, constant head boundaries, constant flux boundaries, and head dependent boundaries. The various boundary conditions in FEFLOW can be constrained by head or flux to represent conceptual boundaries such as drains or streams. The constraints are limitations which result from the requirement that the boundary condition is only valid as long as minimum and/or maximum head or flux bounds are satisfied. If, during a simulation run, the conditions fall below or are exceeded, the constraints are to be assigned as new intermediate boundary conditions. This section is a discussion of the implementation of boundary conditions and constraints in the model.

The boundary locations for a typical model layer and for the PCS are shown on Figure 3-2 and Figure 3-3.

3.3.1 No Flow Boundaries

A no flow boundary was set along the west edge of the model corresponding to the outcrop of the PCS/Lewis shale contact. A no flow boundary was also set in the model layers representing the Fruitland Formation along the east edge of the model where this boundary is parallel to the regional groundwater flow direction. A no flow boundary was also set in the model layers representing the Fruitland Formation along the western portion of the north boundary where the Cottonwood alluvium represents a local discharge area. No flow boundary conditions are shown on Figures 3-2 and 3-3 at locations along the edge of the model domain where no other boundary conditions are present.

3.3.2 Recharge

Recharge in FEFLOW can be treated as a constant flux boundary condition with a constraint that allows flow only into the model, or as a flow into top layer of the model. Constrained boundary conditions can add significantly to the computational time to run the model, so the simplified flow into the top of the model was chosen to represent recharge. The distribution of recharge boundaries is shown on Figure 3-4.

3.3.3 Stream Boundaries

The ephemeral streams (Cottonwood Arroyo, Pinabete Arroyo, No Name Arroyo, and Brimhall Wash) and tributaries are represented as head dependent (Cauchy) boundary conditions constrained such that the boundary removes water when the groundwater elevation is greater than a specified reference head, but that no flow in to the groundwater system is contributed by the boundary. When constrained this way the boundary acts similar to a MODFLOW drain boundary. Drain conductance is specified as a leakage coefficient and was set to a value of 10^{-4}/day. Stream boundaries are shown on Figure 3-2.

3.3.4 Head Dependent (Cauchy) Boundaries

During initial model calibration it became clear that the boundary between the PCS and the Lewis Shale needed to account for vertical flow to support model calibration. Head dependent, or Cauchy, boundary conditions were assigned to each finite element node at the base of model to simulate flow between the PCS and Lewis Shale. These boundary conditions were unconstrained to allow flow into or out of the base of the model.

An effort was made to examine alternate conceptual models for this boundary condition. Several configurations of reference head and leakage coefficient for the boundary conditions were examined to represent the potentiometric surface of the Lewis Shale and vertical hydraulic conductivity between the PCS and the Lewis Shale, respectively. For example, the reference head was first set as the elevation of the base of the PCS with a constant leakage coefficient. Other conceptual models examined included a reference head with a constant slope from south to north and a linear increase in leakage coefficient from west to east.

In the final calibrated model, the reference head is a damped surface based on the elevation of the top of the PCS, and the leakage coefficient varies in space, generally decreasing with the depth to the top of the PCS. The damped reference head surface for the head dependent boundary conditions was determined by choosing a reference elevation contour of the top of the PCS and smoothing the highs and lows in the PCS top based on this reference contour. The final calibrated leakage coefficient is higher on the west side of the model where the PCS is shallower and decreases as the PCS dips to the east. The reference head surface and the distribution of leakage coefficient for the head dependent boundary conditions are shown on Figure 3-5 and Figure 3-6, respectively.

3.3.5 Constant Head (Dirichlet) Boundaries

Constant head, or Dirichlet, boundaries were assigned at finite element nodes where the four main streams intersect the west model boundary. These boundary conditions are constrained by setting a maximum flux constraint equal to zero. With the maximum flux constrained to zero, the boundary condition can only remove water from the model representing stream flow out of the model domain. The locations of these boundaries are shown on Figure 3-2.

Unconstrained constant head boundaries were also assigned along the south edges of the model domain in the layers corresponding to the Fruitland Formation coal seams. These boundaries were assigned the potentiometric head of the PCS and were assigned where the potentiometric head of the PCS was above the bottom of the specific model layers.

In the model layers corresponding to the PCS, constant head boundaries were assigned along the entire lengths of the south, east and north edges of the model domain. The constant head boundaries along the north boundary are constrained such that groundwater can only flow out of the model domain. These boundaries are shown on Figure 3-2 and 3-3.

3.3.6 Flux (Neumann) Boundaries

Constant flux, or Neumann, boundaries were assigned along portions of the north model boundary in layers representing the Fruitland Formation coal seams to represent groundwater flow out of the model domain. Fluxes were determined from regional groundwater gradients and hydraulic conductivities of the individual model layers. The locations of the flux boundary conditions are shown on Figure 3-2, and the constant fluxes assigned to the boundaries in individual layers are shown in Table 3-2.

3.4 UNSATURATED ZONE FLOW IMPLEMENTATION

FEFLOW utilizes a full implementation of Richard's Equation for solving saturated/unsaturated flow problems. The modified Van Genuchten parametric relationship for capillary pressure head and relative conductivity was used to model unsaturated zone flow.

4 MODEL CALIBRATION AND SENSITIVITY ANALYSIS

In multilayer groundwater models, the hydraulic parameters (mainly hydraulic conductivity) of the model layers and boundary conditions (mainly recharge, potentiometric heads, and leakage coefficients) are adjusted during model calibration in order to obtain a better match with observed heads and potentiometric gradients. Model calibration is necessary because hydraulic parameters obtained from well tests, regional studies, or literature values for similar hydrogeologic units are, at best, order of magnitude estimates of the average hydraulic conductivity and storage properties of the hydrogeologic unit on the scale of the model. With reliable estimates for the expected magnitude of either groundwater recharge or groundwater discharge and estimates for the expected upper and lower bounds for hydraulic conductivities of the hydrogeologic units, the model can be constrained during model calibration to arrive at a model that is an acceptable representation of the hydrogeologic system.

Model calibration can also serve to revise the conceptual model of the groundwater system and provide a better assessment of the properties of hydrogeologic units on a regional scale that cannot be obtained solely from local pumping test results. Model calibration is assumed to be achieved once the model reasonably simulates the interpreted groundwater flow conditions in the area of interest using input values that are within the range of measured or estimated values. The primary measures of model calibration are the match between the measured groundwater potentiometric surface (“heads”) and the model’s predicted values at the same location. Other considerations in arriving at an acceptable calibrated model included any model predicted locations of surface saturation, comparison of modeled potentiometric surfaces with potentiometric surfaces developed for the conceptual model. The data used in model calibration and the calibration results are discussed in this section.

4.1 CALIBRATION TARGETS

The calibration targets for the model were measured groundwater elevations in monitoring wells within individual coal seams, in the alluvium and in the PCS. Surface saturation and groundwater potentiometric surfaces were also used as a general guide in model calibration. Table 4-1 lists the calibration wells, formation, model layer, observed potentiometric head, and the calibrated model potentiometric head. The locations of the calibration wells are shown on Figure 4-1.

4.2 STEADY STATE MODEL CALIBRATION

Model calibration was performed by running the model repeatedly with the steady state boundary conditions and using a range of values for model parameters. In order to better match the observed head calibration targets, several model input parameters were varied within acceptable ranges. These parameters included hydraulic conductivity, leakage coefficient for drain and stream boundaries, recharge, and reference head and leakage coefficient for the head dependent boundary condition at the base of the model. Unsaturated zone wetting curve parameters were also varied during model calibration. The final calibrated regional PCS potentiometric surface is shown in Figure 4-2, and the calculated vs. observed heads for all calibration wells is shown in Figure 4-3 and in Table 4-1.

4.3 STEADY STATE MODEL RESULTS

Detailed discussions of the steady-state baseline modeling results are presented in Appendix 6.G of the Navajo Mine PAP. Transient simulation results are dependent upon the specific mine plan being simulated and are included in the PHC assessment supporting the mine permit application. Selected model results are presented below.

4.3.1 Mass Balance and Groundwater Budget

The model mass balance was reviewed as part of the steady state model calibration. The mass balance is the difference between the inflow into the model and the outflow (discharge) from the model. The overall model mass balance difference is 0.24 %. A low mass balance difference is indicative of a lack of numerical issues with the model and that the model is run with adequately small convergence criteria. Various authors recommend that the mass balance difference should be less than 0.1% for saturated groundwater flow models (Konikow 1996) and less than 1% for variably saturated groundwater flow models (USGS 2000).

4.3.2 Potentiometric Surface Contour Maps

The model calibrated PCS potentiometric surface is shown on Figure 4-2. The modeled potentiometric surfaces for the No. 3 Coal and the No. 8 Coal are shown on Figures 6.G-2 and 6.G-3 in Appendix 6.G of the Navajo Mine PAP. The modeled pre-mining potentiometric surfaces generally follow the conceptual model. The modeled steady state results and recharge rates are consistent with the measurements or estimates obtained from baseline monitoring as previously discussed. However, the modeled potentiometric surfaces extend beyond the limits that could be depicted from measurements at monitoring wells and piezometers. For example, the results for the No. 3 Coal in Figure 6.G-2 in Appendix 6.G show groundwater flow toward the topographic lows along the west side of the model domain in the valleys of No Name Arroyo, Pinabete Arroyo, Brimhall Wash, and Cottonwood Arroyo. These results could not be determined from potentiometric measurements alone, which indicate a general potentiometric gradient to the north northeast in the No. 3 coal. A detailed discussion of the steady state model potentiometry is found in Appendix 6.G.

4.4 STEADY STATE MODEL SENSITIVITY ANALYSIS

A sensitivity analysis was performed after model calibration to determine the affect on model calibration of changes in the calibrated model parameters. The model parameters included in the sensitivity analysis were the hydraulic conductivities of the alluvium, the coals, the overburden and interburden, and the PCS; the recharge rate; and the leakage coefficient of the head dependent boundary condition at the base of the PCS. The steady state model was run varying the individual parameters over the ranges shown in Table 4-2. In addition to the formal sensitivity analysis, the effect of other model parameters was noted during model calibration. The results of both of these efforts are discussed in this section. Plots of calculated vs. observed heads resulting from the sensitivity runs are shown in Figures 4-4 through 4-21. The plots show the effect that varying of individual model parameters has on the model calibration.

Figures 4-4 and 4-5 show the results of varying the hydraulic conductivity of the PCS over the range of one-half the calibrated value to twice the calibrated value. A hydraulic conductivity for the PCS of one-half the calibrated value, results in over prediction of most of the head values particularly in the higher head locations as shown in Figure 4-4. A hydraulic conductivity for the PCS of twice the calibrated value does not indicate a particular bias in the head predictions as shown in Figure 4-4 but does result in more scatter in the prediction as indicated by the higher mean absolute (MA) residual. The results show that modeled potentiometric heads in the PCS are somewhat sensitive to the hydraulic conductivity of the PCS, and that the potentiometric heads in the Fruitland Coals are less sensitive to this parameter.

During model calibration it was noted that predicted results were not very sensitive to the horizontal hydraulic conductivity of the lower coals within the calibration range but the results were more sensitive to the horizontal hydraulic conductivity of the upper coals. A hydraulic conductivity for the upper coals of five times the calibrated value results in more scatter as shown in Figure 4-6. The results show that modeled potentiometric heads in the alluvium and the upper coal are very sensitive to the increase in the horizontal hydraulic conductivity of the upper coals. A hydraulic conductivity for the upper coals of half the calibrated value as shown in Figure 4-7 also results in more scatter in the prediction, although the mean absolute (MA) residual is better than the results in Figure 4-6. The results in Figure 4-7 show that modeled potentiometric heads in the alluvium are particularly sensitive to the decrease in the horizontal hydraulic conductivity of the upper coals.

Weathered coals were identified in the upper coal seams (No. 6, No. 7 and No. 8) in the geologic model. Model calibration improved when these weathered coals were assigned a hydraulic conductivity one order of magnitude greater than the unweathered coal. Figure 4-8 provides the sensitivity results performed with the weathered coal hydraulic conductivity equal to that of the unweathered coal. The plot shows much greater scatter in the head prediction in comparison with the calibration results with an MA residual of 25.5 feet in comparison with 11.4 feet for the calibrated model. The results show that modeled potentiometric heads in the PCS and the alluvium are highly sensitive to the hydraulic conductivity of the weathered coals and that the heads in the coals are less sensitive to this parameter. This result is most likely due to the fact that the weathered coals are nearest to the formation outcrops near the alluvium.

During model calibration, the predicted results were found to be sensitive to the vertical hydraulic conductivities of the interburden layers. In particular, a vertical hydraulic conductivity of 1.0 x 10^{-6} ft/day (Kx/Kz = 500) was needed for the interburden layer between the No. 6 coal and the No. 4 coal in order simulate the large vertical head gradients between the upper coal seams and the lower coal seams. Sensitivity model runs were made with Kz for this interburden zone (layer 14) adjusted to 5 x 10^{-6} ft/day (Kx/Kz = 100) and to 5 x 10^{-7} ft/day (Kx/Kz = 1,000). These results are provided in Figures 4-9 and 4-10 respectively, and show that the results are highly sensitive to the vertical hydraulic conductivity of the interburden layer separating the upper coals from the lower coals, particularly the predicted heads in the alluvium and the upper coals units.

Sensitivity runs were made with vertical hydraulic conductivity, Kz, of the interburden layers separating the upper coals (No. 6, No. 7 and No. 8 coals) decreased from 5.0 x 10^{-6} ft/day (Kx/Kz=100) to 2.0 x 10^{-7} ft/day (Kx/Kz=2,500) as shown in Figure 4-11. Figure 4-12 provides the plot of predicted versus observed head with the vertical hydraulic conductivity, Kz, of the interburden layers separating the upper coals (No. 6, No. 7 and No. 8 coals) increased from 5.0 x 10^{-6} ft/day (Kx/Kz=100) to 2.5 x 10^{-5} ft/day (Kx/Kz=20). These plots show the model calibration to be much less sensitive to these changes in the Kx/Kz ratios of the interburden within the upper coals in comparison with the Kz separating the upper coals from the lower coals.

The model calibration was even less sensitive to the Kz of the interburden layers between the lower coals (No. 2, No. 3 and No. 4 coals). Figure 4-13 shows the relative minor decrease in the MA residual when the Kz of the interburden layers between the lower coals is decreased from 2.0 x 10^{-5} ft/day (Kx/Kz=25) to 2.0 x 10^{-7} ft/day.

Figures 4-14 through 4-16 show the results of varying the hydraulic conductivity of alluvium in Cottonwood Wash, Pinabete Arroyo, No Name Arroyo, and Brimhall Wash. The results show that the modeled potentiometric heads in the coal layers are highly sensitive to the hydraulic conductivity of the alluvium. The heads in the PCS are also sensitive to this parameter, but less so than the heads in the coals. The best calibration was with a hydraulic conductivity for the alluvium of 156 ft/day, which is above the hydraulic conductivity of the alluvium expected from aquifer test information provided in Attachment 1. Despite the relatively fine mesh depicted in Figure 3-1, the alluvium is often represented by a width of one or two elements along the length the alluvium. The finite element calculation essentially averages the hydraulic conductivity from elements adjacent to the nodes to calculate the head at the node. This averaging occurs in both the horizontal and vertical dimensions. Due to this averaging effect, a higher hydraulic conductivity needs to be assigned to the elements representing alluvium to compensate for the lower hydraulic conductivity of the adjacent elements or a finer mesh is needed to transition between the alluvium and the adjacent bedrock.

During the model calibration process it became evident that the calibration was also highly sensitive to the reference head and the leakage coefficient of the head dependent boundary at the base of the model which represents groundwater interaction between the PCS and the Lewis Shale. The reference head of this boundary condition represents the potentiometric head in the Lewis Shale, and the leakage coefficient is a function of the vertical hydraulic conductivities and thicknesses of the two formations. The effect of these parameters on model calibration appears to be highly coupled, therefore, only the leakage coefficient was varied in the sensitivity analysis. In the calibrated model, the leakage coefficient ranged over the model domain from 4×10^{-9}/day to 3×10^{-8}/day (Figure 3-6). In the sensitivity analysis, the leakage coefficient was ranged from one-half to twice the calibrated value. These results are shown in Figures 4-17 and 4-18, respectively. An additional sensitivity run was made with a constant leakage coefficient of 3×10^{-8}/day as shown in Figure 4-19. The residual plots resulting from varying the leakage coefficient of the head dependent boundary at the base of the model show that the model calibration is highly sensitive to this parameter.

In addition to the sensitivity runs discussed above, model calibration runs revealed a high sensitivity to the recharge rates of the various surface characterizations in Table 2-2 (particularly, the upland flat recharge rate). Figures 4-20 and 4-21 show plots of the results of varying the recharge rates in the model from 0.8 to 1.2 times the calibrated values. The recharge parameters are the main parameters that control flow into the groundwater system over the model domain. Hence, the model calibration is very sensitive to these model parameters.

4.5 TRANSIENT MODEL SENSITIVITY ANALYSIS

The calibrated steady state model is applied to simulate the transient response to mining. This application requires that the storage characteristics of the hydrogeologic units within the model domain be defined. It also assumes that the transient behavior can be simulated adequately without transient model calibration. As mining progresses the observations of drawdown at monitoring wells will provide the transient response that can be used to revise the model calibration for future predictions if previous predictions are off.

The groundwater drawdown and recovery resulting from mining and reclamation was simulated using the FEFLOW default specific storage value of 10^{-4} per foot and default specific yield of 0.2

and using the specific storage values and specific yield values for the various units as determined in Attachment 1 (Base case). Figure 4-22 shows the differences in the drawdown and recovery in the backfill and in the PCS at the two locations Y3 and Y5 that result using the FEFLOW default values and the Base case estimates for the various units. The Y3 and Y5 locations are shown in Figure 4-23 and represent locations within the year-3 mine pit and the year-5 mine pit. The results in Figure 4-22 show that the FEFLOW default values simulate less drawdown but slower rates of recovery in both the PCS and the mine backfill in comparison with the Base case estimates. The drawdown and recovery response also varies spatially with greater drawdown at the Y3 location relative to the Y5 location.

In addition, the sensitivity analysis of the extent of drawdown to changes in specific storage and specific yield were assessed using the FEFLOW default values and the Attachment 1 estimates of specific storage and specific yield for the various units. The maximum extent of the 5 foot drawdown for the No 8 coal for the two simulations is shown in Figure 4-23. These results show that the drawdown extent in the upper coals is not particularly sensitive to changes in the specific storage and specific yield However the drawdown extent in the deeper coals and in the PCS is more sensitive to the changes in specific storage and specific yield as shown in Figures 4-24 and 4-25, respectively

4.6 MODEL LIMITATIONS AND USES

As with any model of a complex physical system, the groundwater model has limitations and uncertainties. Simplifying assumptions must be made to model the complex hydrogeologic system. In particular, the hydrogeologic units within the model domain have been represented as homogeneous and isotropic. Geologic environments are never homogeneous and isotropic. However, such assumptions are required because it is not possible to define hydraulic conductivities, specific storage, specific yield, porosity and other properties spatially within all the hydrogeologic units within the model domain.

The groundwater model assumes that Darcy's law and the equations of flow through porous media apply to the strata at the site. However, almost all the bedrock sedimentary deposits and coals within the model domain have low matrix permeability and are fractured. Groundwater flow is typically through fractures, bedding-plane partings, and coal cleats and to a much lesser degree through the intergranular pores. Low permeability units (such as the claystones, the shales and in many cases the sandstones) also exert significant control on groundwater flow. The facies, fractures and hydrogeologic properties of these units all vary spatially. At best, the properties of particular hydrogeologic units can be determined from site testing and adjusted during model calibration to arrive at a model that adequately represents the general behavior of the hydrogeologic system.

Model calibration produces a non unique solution and there are a number of calibrations that could be selected on the basis of comparable measures of head residuals. Furthermore, it would have been possible to arrive at a better calibration by spatially varying the hydraulic conductivities for the various hydrogeologic units within the model domain. However, adjustments to improve calibration were not performed unless there was supporting geologic information for such spatial adjustment. The geologic model provided a fairly clear delineation between the weathered coals and the non-weathered coals. As such, the delineated weathered coals were the only locations, where the hydrogeologic properties were adjusted spatially during model calibration to values that were different from the corresponding coal unit.

The hydrogeologic unit within the model domain that is believed to include the greatest uncertainty in the model simulations is the alluvium within the valleys of Cottonwood, Pinabete and Brimhall. Part of this uncertainty is due to the difficulties in delineating the extent and depth of alluvium and representing that delineation by the finite element mesh. Also, the baseline information shows that the groundwater within the alluvium is not at steady state as is assumed in the calibration of the steady state model. Groundwater flows, groundwater levels and groundwater recharge within the alluvium varies seasonally and from year to year. Perched conditions also occur within some segments of the alluvium as indicated by the well nest adjacent to Pinabete Arroyo. All of these conditions add to the uncertainty in the predictions within the alluvium based on the calibrated steady-state groundwater model.

Despite these limitations, the model provides a better understanding of the hydrogeologic system and the nature of the changes in the system that might occur as a result of mining and reclamation. The model predictions are essentially scientific hypotheses that will be re-examined as mining and reclamation proceed. The model is a useful tool for evaluating the possible extent and magnitude of changes in the hydrogeologic system that might occur in response to proposed mining and reclamation. The model is also useful in identifying the time frames that might be associated with these changes. These results provide better insight into the locations and frequency of monitoring that can be used to confirm or modify the PHC predictions.

Groundwater monitoring has been performed at various locations within the vicinity of the site over the past forty years. These monitoring results show very little change in the hydrogeologic conditions in the bedrock units over these time frames. Transient model simulations also show that the response in the bedrock units beyond the direct impact area of mining is very slow and damped. Nevertheless, model predictions far beyond the historic monitoring period need to be considered in the context of other changes that might be influencing the hydrogeologic system in the long-term to avoid false confidence in model predictions far into the future.

5 SIMULATION OF PROPOSED MINING AND RECLAMATION

5.1 STEADY STATE POST MINING CONDITIONS

For the PHC modeling scenario, mine backfill properties were added to the mined out area associated with the Area IV North mine plan. The overburden and interburden material placed in the mine pit as backfill will have higher porosity and hydraulic conductivity than the pre-mine interbedded sedimentary deposits of the Fruitland Formation. Laboratory measurements of pre-mine overburden core indicate porosity values of about 0.35 while porosity of mine spoils is on the order of 0.40. These laboratory porosity measurements are consistent with the swell factor of 12% estimated based on experience in mining the same formation at the Navajo Mine. The higher porosity will result in higher hydraulic conductivity in comparison with the pre-mine interburden and overburden material (Van Voast, 1974).

A detailed discussion of the steady state model simulation results for post-mining conditions following proposed mining within Area IV North is presented in Section 11.6.2.4 of the Navajo Mine PAP. Comparison of the steady state pre-mine and post-mining groundwater model results show the changes in the groundwater flow patterns and rates that are expected to occur in the long-term following mining. These results support the quantitative assessments of the potential changes in regional or local aquifers resulting from mining. In particular, these effects include the removal of the interbedded coal, shales and sandstone strata and replacement with a relatively homogeneous and isotropic spoil backfill and the increase in recharge rates for reclaimed surfaces. The steady state pre-mine groundwater model simulates a large decline in heads with depth in the Fruitland Formation, including the occurrence of perched groundwater zones. After mining, the simulated steady state heads in the mine spoil are much more uniform with depth, although there is still a slight downward gradient and downward flow. Also, the perched groundwater that occurs under pre-mine conditions within the mine area is eliminated within and near the spoil backfill under long-term steady state conditions following mining. Both the pre-mine and post-mine steady state groundwater flow models show a flow component from Area IV North toward the topographic low elevations along Cottonwood Arroyo in the PCS and in the Fruitland Formation coals. The rate of groundwater flow toward these topographic lows increases for post-mining conditions due to the increase in recharge rate within the reclaimed mine areas.

5.2 TRANSIENT MODEL SIMULATIONS

For the transient simulations of proposed mining operations in Area IV North, detailed mine progression plans were lumped into one-year time increments with constant head boundaries set to the base of mining in all mined out layers over the area covered by the specific one-year time increment (i.e. for a one-year time increment, the entire area of the one-year plan was simulated as dewatered over the one year increment). The proposed plan for pit advance within Area IV North from year 2011 to year 2016 is shown in Figure 11-39 in Chapter 11 of the Navajo Mine PAP. The transient model was run for 500 years after the completion of mining to simulate post-mining transient behavior. A recharge rate of 0.10 in/year was used for mine spoils in the transient modeling until final reclamation, after which the long-term recharge rate of 0.04 in/year was used for reclaimed areas in the transient model. This recharge rate of 0.10 in/year used for mine backfill and initial reclamation in the transient simulations represents an average rate for the mine backfill in various stages of reclamation and is based on the average between Stone's estimate of 0.16 in/year for depressions during mine reclamation and the 0.04 in/year for final reclamation.

5.2.1 Transient Model Parameters

The area covering the one-year increment being mined was assigned hydraulic properties to simulate "air" in the open pit. The specific yield and specific storage in these areas were set equal to 1, and hydraulic conductivity was set equal to 8,640 ft/d. As one increment ended and the next was started, mine backfill hydraulic parameters were added to the model over the area of the previous one-year increment. As discussed in Section 5.1, swelling of mine backfill is accompanied by an increase porosity and permeability, therefore, hydraulic conductivity and storage properties were increased in the transient simulations compared with those used in the steady state pre- mining runs. Mine backfill properties are shown in Table 5-1. The hydraulic conductivity of 0.0113 ft/day ($4.0\text{x}10^{-6}$ cm/sec) estimated from laboratory tests on Navajo Mine spoils was used as a lower bound estimate for mine spoils to provide more conservative estimates of water recovery rates in mine spoils.

5.2.2 Initial Conditions

The head and saturation distributions from the pre-mining steady state simulation were used as initial conditions for the first one-year transient run in the mine plan. Subsequent one-year transient runs used the final result of the prior year run as initial conditions. At the conclusion of the proposed Area IV North mine plan, the final mine area was assigned backfill properties and a post mining transient simulation was run for 500 years to simulate rebound in groundwater levels in the mine backfill.

5.2.3 Transient Model Results

The results of the transient mining simulations are discussed in Section 11.6.2.4 of the Navajo Mine PAP. The transient modeling results presented in Section 11.6.2.4 of the Navajo Mine PAP show the slow rate of spoils resaturation as well as the rate of drawdown and recovery in the coals and PCS adjacent to mining.

5.3 MASS TRANSPORT MODEL SIMULATIONS

The FEFLOW software used for groundwater flow modeling also includes features that simulate conservative and reactive transport. The FEFLOW transport routines were applied to simulate the transport of TDS as a conservative constituent from mine spoil materials that are planned for backfilling of mine pits. TDS was selected for transport modeling based on analysis of constituents in spoil monitoring wells and spoil leaching tests as described in Section 11.6.2.4.3 of the Navajo Mine PAP. TDS transport modeling simulations were performed using a lower bound source concentration of 3,550 mg/l and an upper bound TDS concentration of 11,850 mg/l. TDS was assumed to behave conservatively, that is with no attenuation due to adsorption or chemical transformation. Sulfate was not modeled separately but was assumed to vary with TDS based on the sulfate-TDS ratio in the source. Based on the observations at the spoil well Bitsui-5, sulfate concentrations are expected to comprise about 41% of the TDS.

The transport model solves advection-dispersion equations of transport processes in groundwater flow. Natural background concentrations were not included in the transport modeling because the objective of the transport modeling is to simulate the direction and rate of transport of modeled constituents from the mine spoils, including the magnitude of attenuation due to dispersion. Mass transport simulations were run for 500 years after the completion of mining assuming that the TDS source concentrations remain constant throughout the 500-year transport modeling period. The 500-year transport simulation was performed using the post-mine steady-state groundwater flow conditions as the initial condition for transport modeling. Experience from other surface mining operations as well as the successive leaching test results indicate that the concentrations of TDS are expected to decline over time with leaching of the mine spoils. A 500-year simulation period was considered reasonable for modeling the fate and transport from a constant TDS source concentration in the backfill. After 500 years it is expected that the source concentrations in the mine backfill will decline as groundwater flows through the mine backfill and flushes salts that may have been concentrated in the mine spoils as a result of weathering and evaporation during mining and backfilling operations.

5.3.1 Initial Conditions

The results of the steady state post-mining flow simulation were used as the initial flow condition for the transport simulations.

5.3.2 Mass Transport Boundaries

Transport runs for TDS were performed assuming that the source concentrations in mine spoils remained constant throughout the 500-year transport modeling period. Constant concentration boundary conditions were assigned to mine backfill for the runs simulating constant leaching to groundwater over time. These constant concentration boundary conditions were assigned concentrations equal to the initial source concentrations as described above.

5.4 MASS TRANSPORT MODEL RESULTS

Mass transport modeling results for the PHC for the proposed mine area in resource Area IV North are presented in Section 11.6.2.4.3 of the Navajo Mine PAP. The transport simulations based on the assumption that source concentrations remain constant throughout the 500-year simulation period show a substantial reduction in concentrations due to dispersion and mixing. Transport modeling results show that lateral migration of groundwater flow and constituents from the mine backfill in Area IV North is primarily vertically downward to the PCS and laterally toward the alluvium and topographic lows along Cottonwood Arroyo.

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TABLES

TABLE 2-1. HYDRAULIC CONDUCTIVITY OF MODEL LAYERS AND CORRESPONDING HYDROSTRATIGRAPHIC UNITS

Formation	Estimated Kx Range		Calibrated Results			Comment
	Kx (ft/d)	Kx (ft/d)	Kx (ft/d)	Kx/Kz	Kx[1] (ft/d)	
Alluvium	5.13E+01	1.15E+01	1.56E+02			
No Name Alluvium			3.11E+01			
Weathered Overburden			5.02E-03	1		
Overburden	1.43E-03	9.64E-04	1.00E-03	10		
S8 Coal	6.00E-02	4.00E-03	1.25E-02	125	1.25E-01	Kz of weathered coal 5.0E-02
Interburden	8.64E-03	2.80E-05	5.01E-04	100		
S7 Coal	8.00E-03	2.00E-03	2.49E-03	2.5	2.49E-02	Kz of weathered coal 1.0E-02
Interburden	8.64E-03	2.80E-05	5.01E-04	100		
S6 Coal	2. 0E-03	1.0E-04	1.88E-03	2.5	1.88E-02	Kz of weathered coal 7.5E-03
Interburden	8.64E-03	2.80E-05	5.01E-04	500		
S4 Coal	2.0E-03	1.0E-0	1.88E-03	2.5		
Interburden	8.64E-03	2.80E-05	5.01E-04	25		
S3 Coal	2.0E-03	1.0E-04	4.99E-03	5		
Interburden	8.64E-03	2.80E-05	5.01E-04	25		
S2 Coal	2.0E-03	1.0E-04	1.25E-03	2.5		
Interburden	8.64E-03	2.80E-05	5.01E-04	25		
Pictured Cliffs Sandstone	4.41E-02	1.00E-04	1.00E-02	1		

[1] **calibrated Kx for weathered coals**

TABLE 2-2. RECHARGE VALUES AND SURFACE CHARACTERIZATION

Surface Characterization	Recharge Range[1] (in/yr)	Mean Recharge[1] (in/yr)	Modeled Recharge (in/yr)
Badlands	0.002 to 0.01	0.006	
Slopes > 5%			0.002
Slopes: 2 to 5%			0.01
Upland Flat	.02 to 0.05	0.03	
Upland Flat (slope<1%)			0.03
Upland (Slope 1 to 2%)			0.02
Alluvial Valley	0.09	0.09	0.09
Mine Backfill			0.04

[1] From Stone, W. J. 1987. Phase-III Recharge Study at Navajo Mine

TABLE 3-1 MODEL LAYERS AND CORRESPONDING HYDROSTRATIGRAPHIC UNITS

Layer	Slice	Formation
1	1	Alluvium and Weathered Overburden
2,3	2,3	Overburden
4	4	S8 Coal
5,6,7	5,6,7	Interburden
8	8	S7 Coal
9,10,11	9,10,11	Interburden
12	12	S6 Coal
13,14,15	13,14,15	Interburden
16	16	S4 Coal
17,18,19	17,18,19	Interburden
20	20	S3 Coal
21,22,23	21,22,23	Interburden
24	24	S2 Coal
25,26	25,26	Interburden
27,28	27,28,29	Pictured Cliffs Sandstone

TABLE 3-2. FLUXES ASSIGNED TO CONSTANT FLUX BOUNDARY CONDITIONS

Model Layer	Coal Seam	Constant Flux (ft/d)
4	#8	1.704×10^{-4}
8	#7	8.52×10^{-6}
12	#6	6.375×10^{-5}
16	#4	6.375×10^{-5}
20	#3	8.52×10^{-5}
24	#2	4.25×10^{-6}

TABLE 4-1. CALIBRATION DATA

Well	Formation	Model Layer	Observed Head	Calibrated Head	Residual
QACW-2B	Alluvium	1	5235.20	5224.97	-10.23
PA-1	Alluvium	1	5340.81	5319.97	-20.84
PA-2	Alluvium	1	5422.73	5403.40	-19.33
KF2007-01	#8 Coal	4	5392.01	5403.41	11.40
KF84-22A	#8 Coal	4	5270.49	5258.15	-12.34
VWP2007-02	#8 Coal	4	5393.67	5403.45	9.78
KF84-21C	#7 Coal	8	5273.98	5240.47	-33.51
KF84-22B	#7 Coal	8	5268.95	5256.52	-12.43
VWP2007-02	#7 Coal	8	5370.81	5389.16	18.35
KF84-22C	#6 Coal	12	5257.20	5255.42	-1.78
VWP2007-01	#6 Coal	12	5329.88	5347.48	17.60
KF84-22D	#3 Coal	20	5248.20	5249.50	1.30
KF-98-02	#3 Coal	20	5354.47	5364.56	10.09
KF-98-03	#3 Coal	20	5291.94	5327.26	35.32
VWP2007-01	#3 Coal	20	5278.56	5281.84	3.27
VWP2007-02	#3 Coal	20	5287.85	5325.76	37.92
KF-98-04	#3 Coal	20	5288.48	5301.90	13.42
KF84-21A	#2 Coal	24	5240.95	5243.31	2.36
KF84-22E	#2 Coal	24	5246.90	5249.37	2.47
VWP2007-01	#2 Coal	24	5273.37	5281.64	8.27
VWP2007-02	#2 Coal	24	5291.09	5325.54	34.45
VWP2007-03	#2 Coal	24	5357.60	5362.06	4.46
VWP2007-5	#2 Coal	24	5410.61	5421.95	11.35
GM-19	PCS	28	5265.00	5272.31	7.31
GM-20	PCS	28	5333.00	5312.87	-20.13
GM-21	PCS	28	5428.00	5439.27	11.27
GM-29	PCS	28	5305.00	5310.11	5.11
GM-30A	PCS	28	5387.00	5385.22	-1.78
KPC2007-01	PCS	28	5262.00	5280.46	18.46
KPC2007-02	PCS	28	5351.90	5360.50	8.60
KPC2007-03	PCS	28	5336.52	5326.88	-9.64
KPC-98-01	PCS	28	5288.31	5271.78	-16.53
T4-1	PCS	28	5385.85	5385.29	-0.56
T4-2	PCS	28	5385.20	5385.31	0.11
O-1	PCS	28	5422.00	5426.77	4.77
13-7-2	PCS	28	5402.00	5410.29	8.29
P-1	PCS	28	5430.00	5439.69	9.69

VWP2007-01	PCS	28	5268.30	5280.44	12.14
VWP2007-02	PCS	28	5296.81	5325.25	28.44
VWP2007-4	PCS	28	5397.48	5404.55	7.07
VWP2007-5	PCS	28	5411.26	5419.03	7.77
GM-28	PCS	28	5265.00	5251.82	-13.18

TABLE 4-2.
Model Parameters Varied in Sensitivity Analysis of Steady State Model

Model Parameter	Calibrated Value	Sensitivity Analysis Range
Alluvium Kx	155 ft/d	31 to 187 ft/d
Upper Coals (#6, #7 and #8) Kx	Variable	Calibrated Value x 5, Calibrated Value / 2
Upper Coal Interburden Kx/Kz Ratio	100/1	20/1 to 2,500/1
Lower Coal Interburden Kx/Kz Ratio	25/1	25/1 to 2,500/1
Interburden between Upper and Lower Coals Kx/Kz Ratio	500/1	100/1 to 1000/1
PCS Kx	0.01 ft/d	0.005 to 0.02 ft/d
Leakage Coefficient of Head Dependent Boundary at Base of Model	Variable	$3\text{x}10^{-4}$/day, Calibrated Value x 2, Calibrated Value / 2
Kx of Weathered Coal	Variable	Kx same as unweathered
Recharge	Variable	Calibrated Values x 0.8 Calibrated Values x 1.2

TABLE 5-1.
RECHARGE RATES AND HYDRAULIC PROPERTIES OF MINE SPOILS FOR POST-MINE GROUNDWATER MODEL

Surface Characterization	**Recharge Range[1] (in/yr)**	**Mean Recharge[1] (in/yr)**	**Modeled Recharge (in/yr)**
Reclaimed Areas	0.01 to 0.23	0.04	
Reclaimed Depression Areas		0.16	
Reclaimed Areas-Transient			0.1
Reclaimed Areas-Steady State			0.04
Alluvium- Pre-Mine and Reclaimed	0.09		0.09
Pre-Mine Surfaces	0.002 to 0.04		0.02

Reclamation Materials	**Porosity (%)**	**Ksat (cm/sec)**	**Ksat (ft/day)**
Surface Mine Spoils (L1)	40.6	2.0E-04	0.563
Mine Spoils <L1	40.6	2.0E-05	0.0563
Geometric Mean of Mine Spoils in Northern Great Plains (Rehm et al, 1980)		8.0E-05	0.2268
Lab Tests of Navajo Mine Spoil Samples	40.6	4.0E-06	0.0113

[1] Estimates from Stone (1987)

FIGURES

FIGURE 1-1. PICTURED CLIFFS SANDSTONE CONCEPTUAL GROUNDWATER MODEL

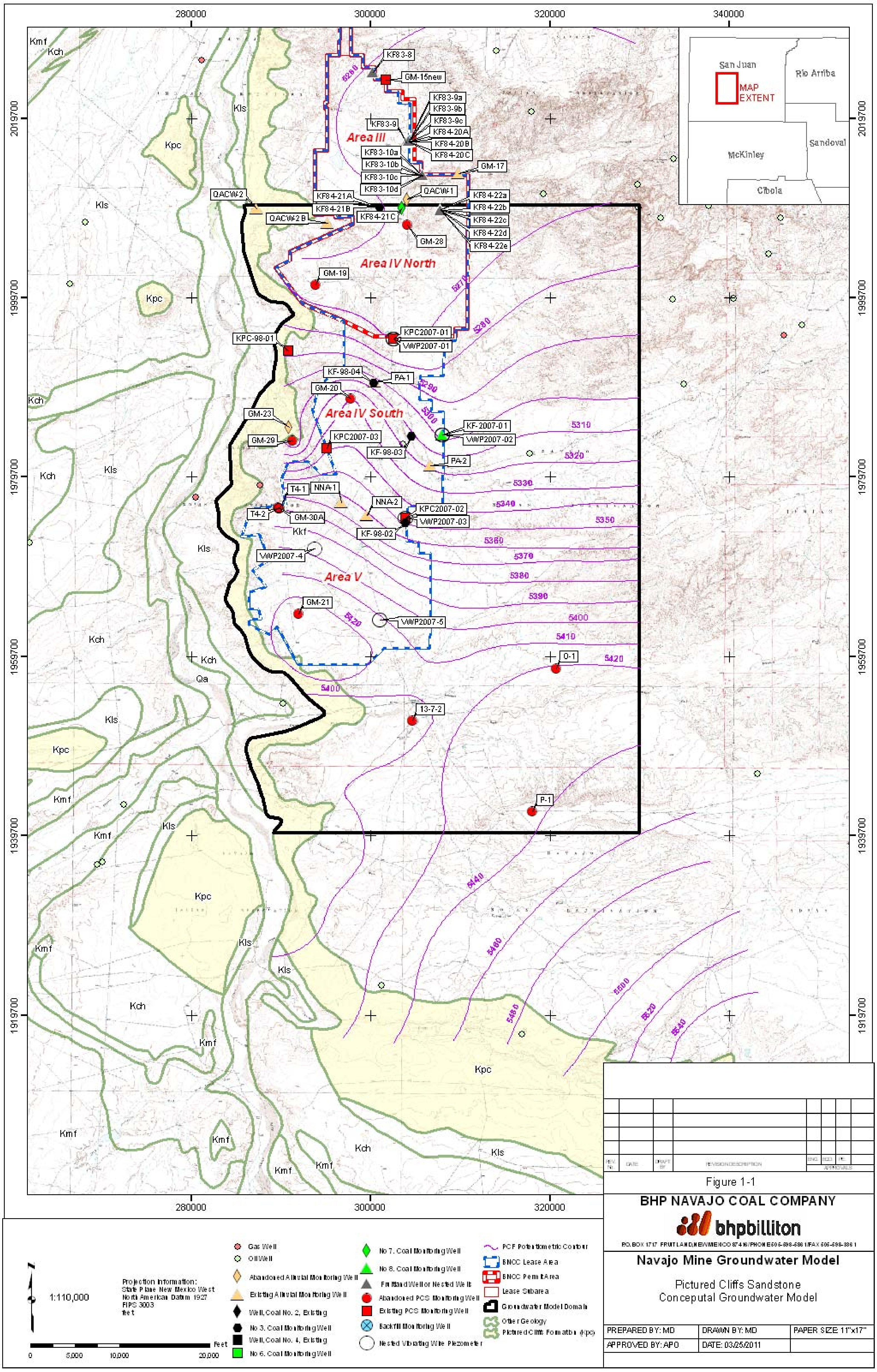


FIGURE 3-1. MODEL DOMAIN AND MESH DISCRETIZATION

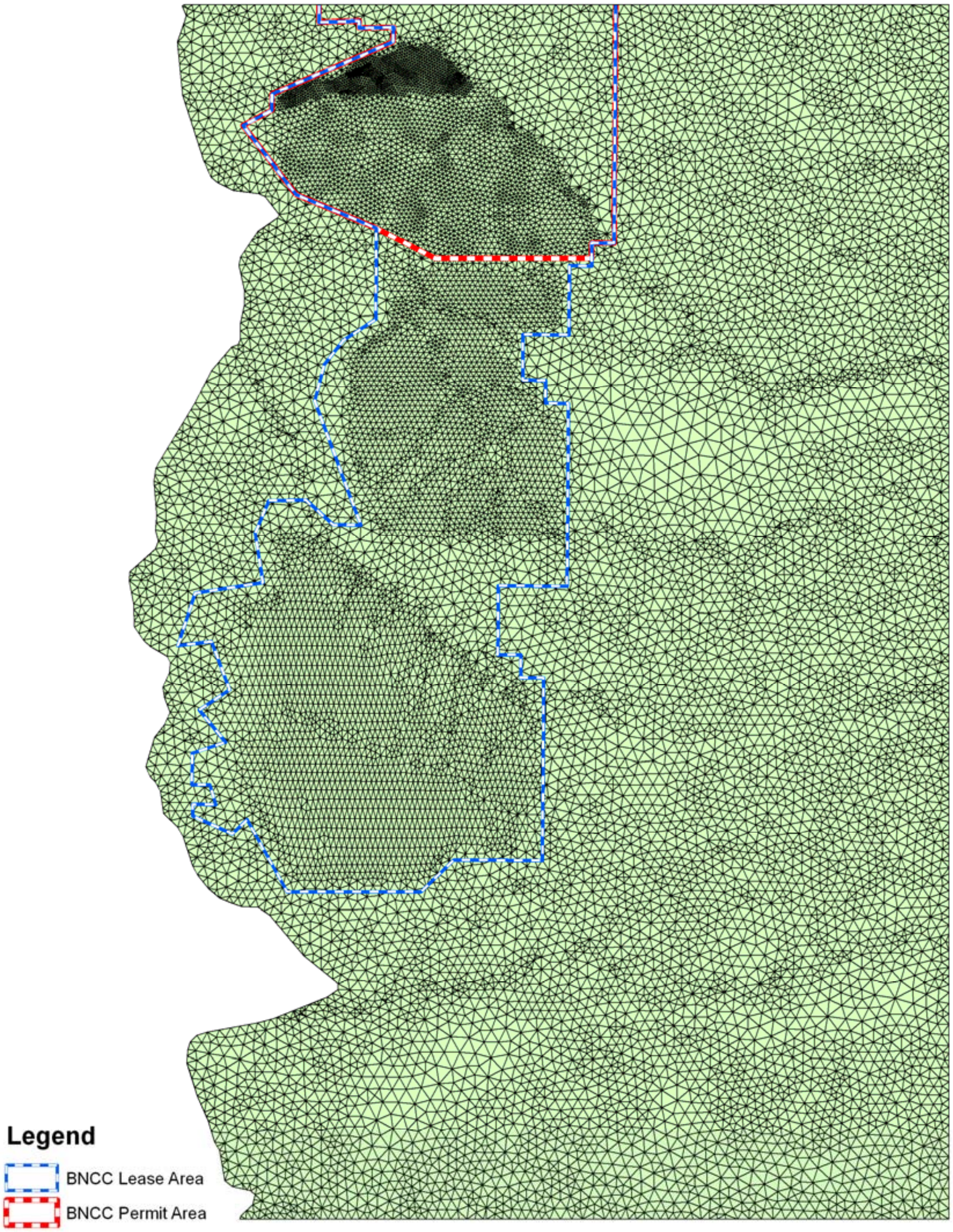


FIGURE 3-2. LOCATIONS OF BOUNDARY CONDITIONS - TYPICAL MODEL LAYER

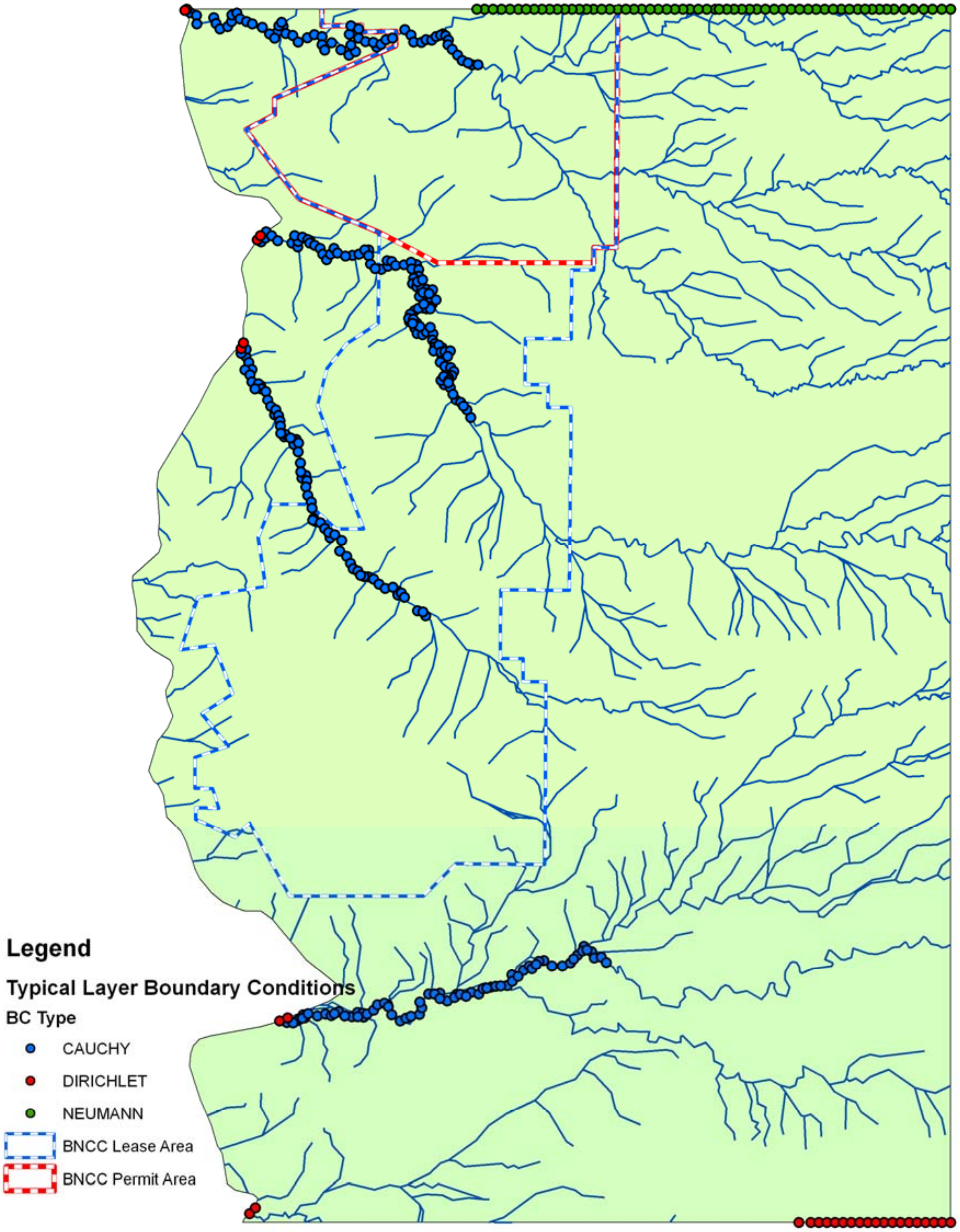


FIGURE 3-3. LOCATIONS OF BOUNDARY CONDITIONS - PCS

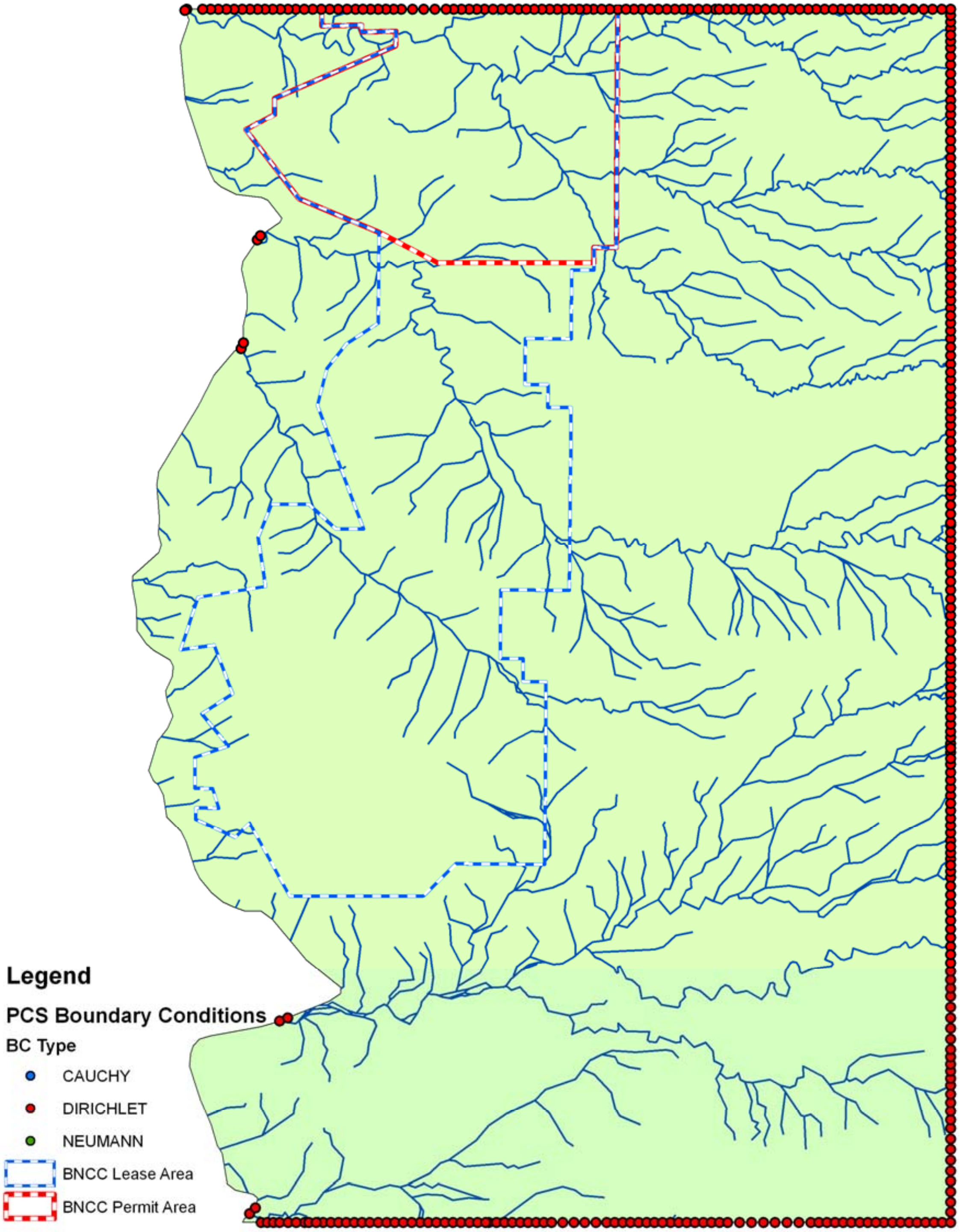


FIGURE 3-4. RECHARGE DISTRIBUTION

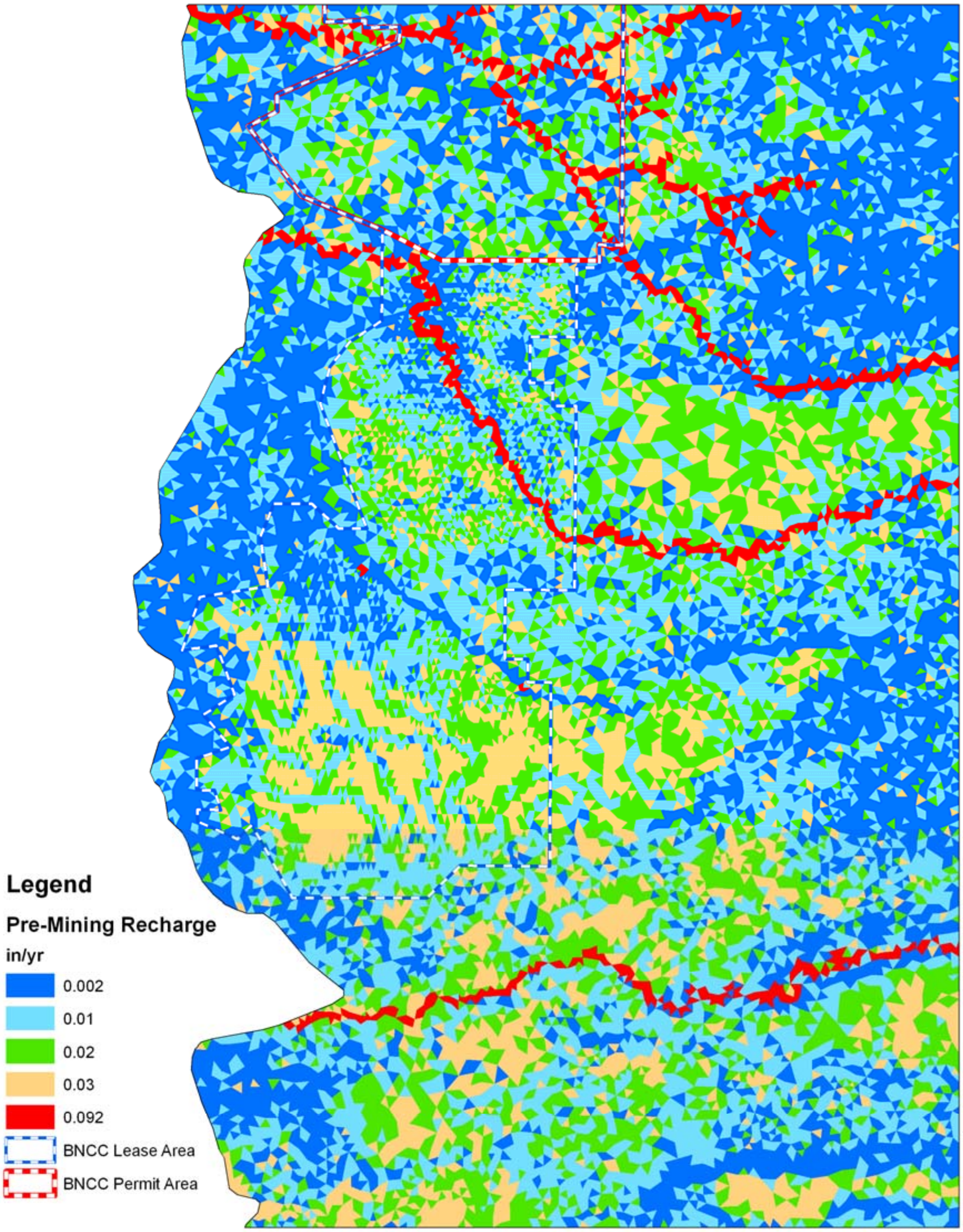


FIGURE 3-5. HEAD DEPENDENT BOUNDARY CONDITIONS - REFERENCE HEAD

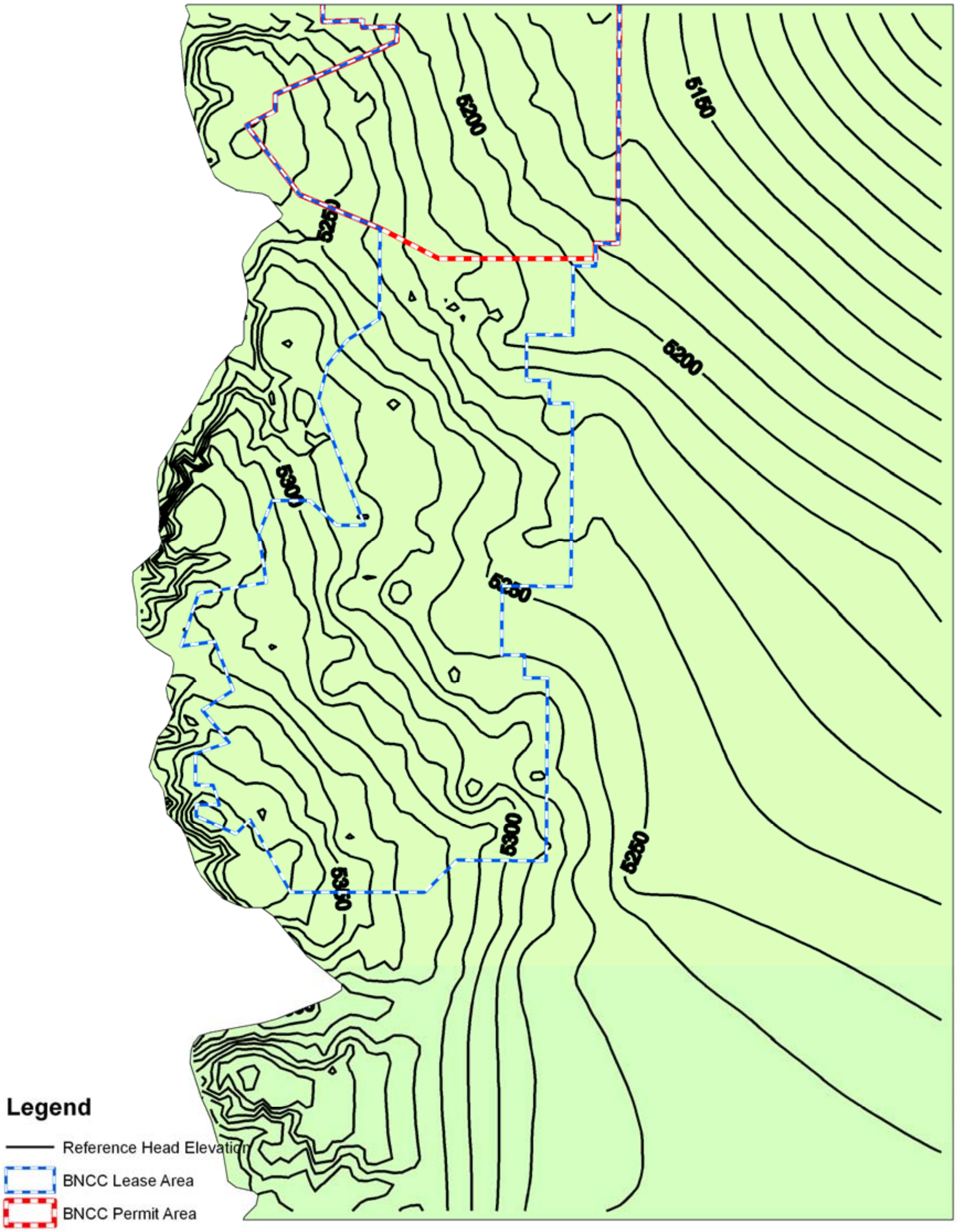


FIGURE 3-6. HEAD DEPENDENT BOUNDARY CONDTIONS - LEAKAGE COEFFICIENT

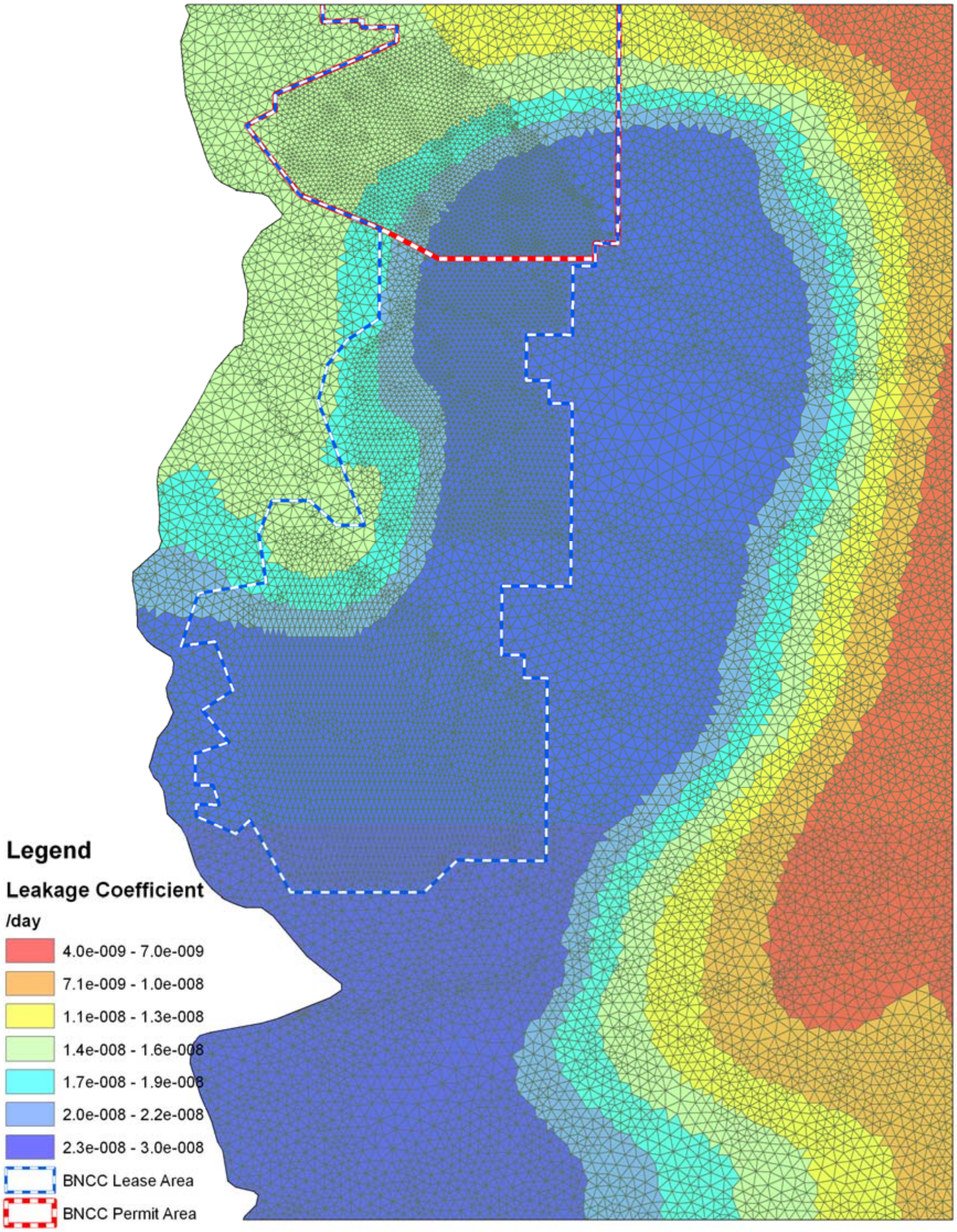


FIGURE 4-1. CALIBRATION WELL LOCATIONS

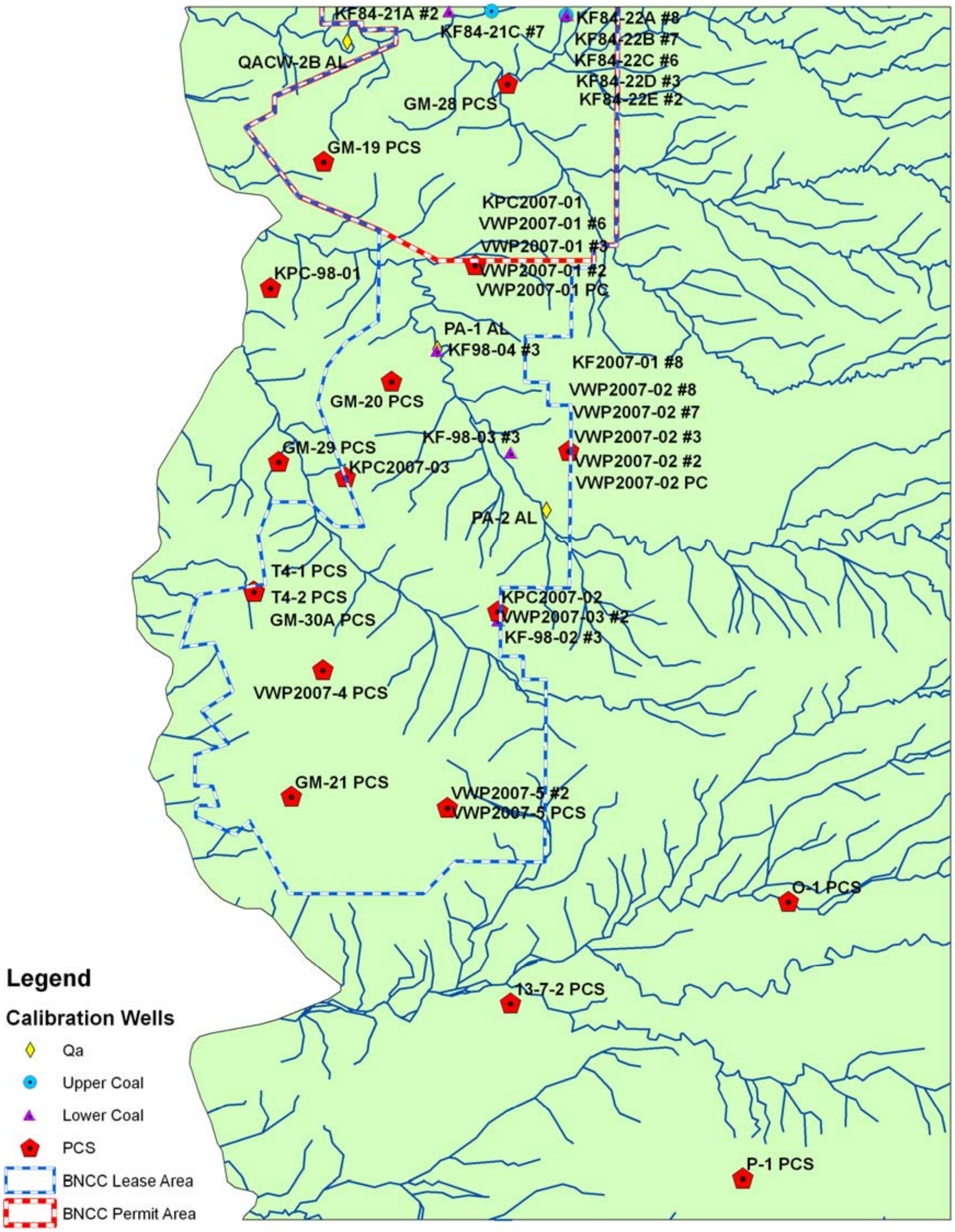


FIGURE 4-2. CALIBRATED PCS POTENTIOMETRIC SURFACE

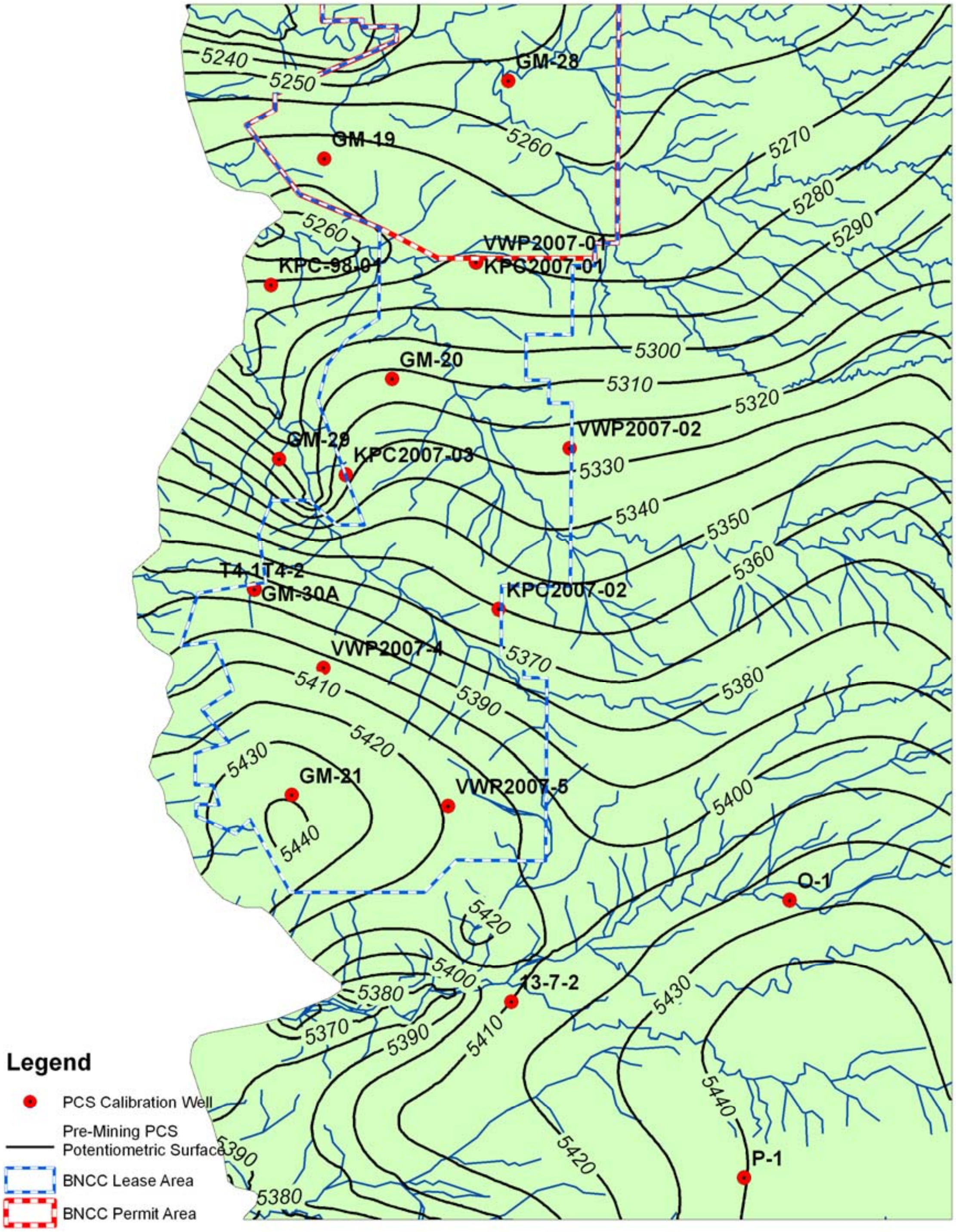
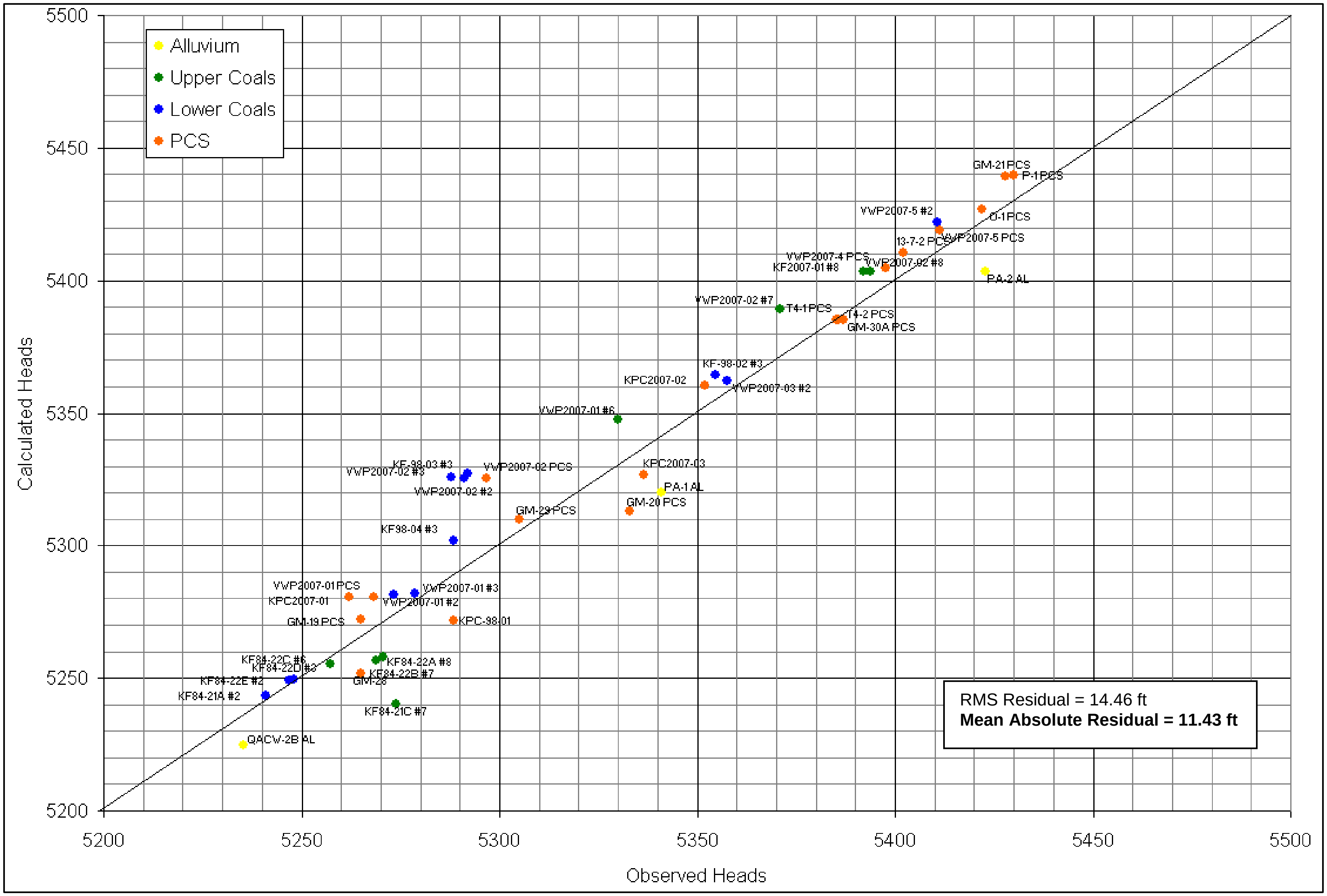
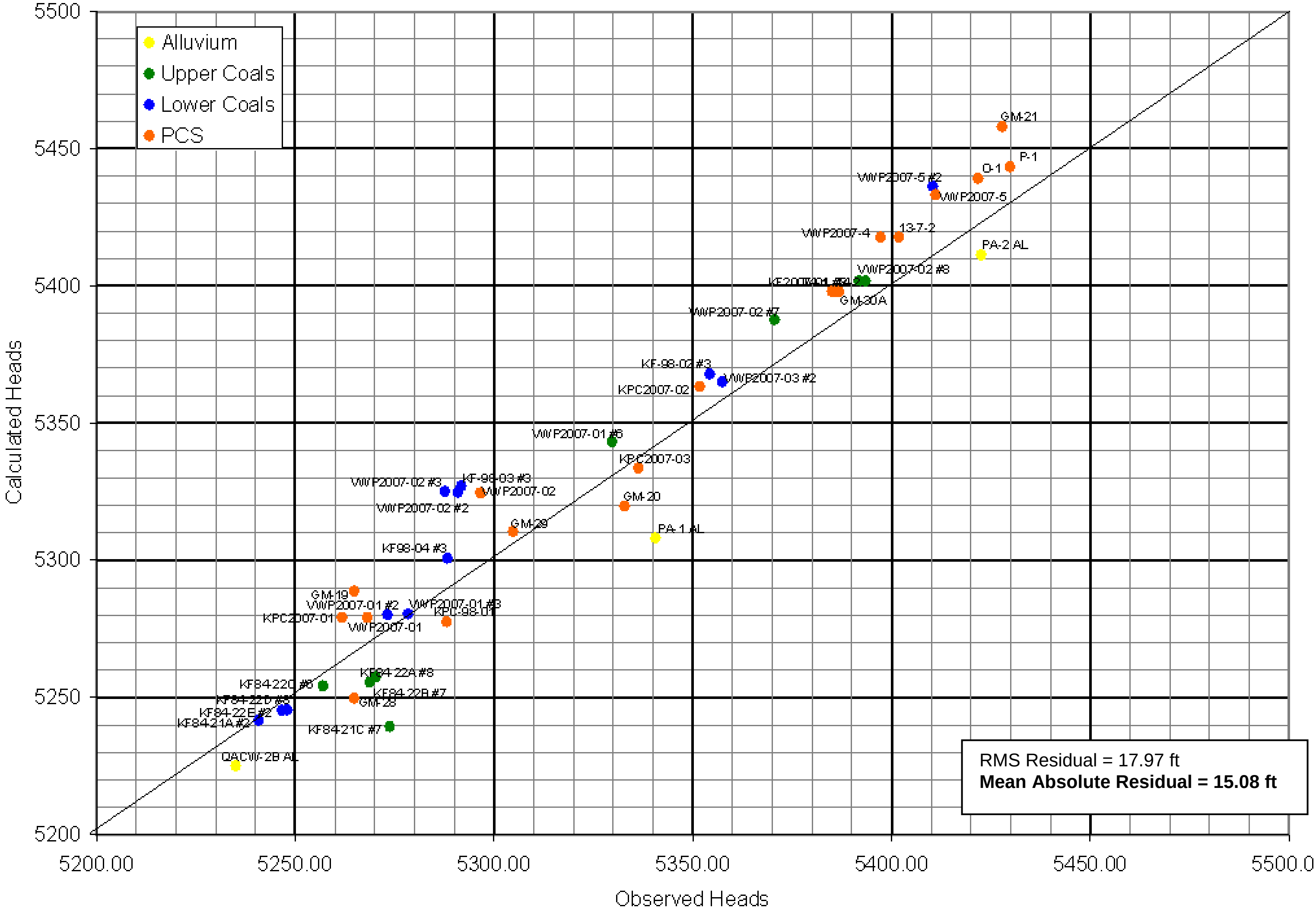


FIGURE 4-3. MODEL CALIBRATION - CALCULATED VS. OBSERVED HEADS



RMS Residual = 14.46 ft
Mean Absolute Residual = 11.43 ft

FIGURE 4-4. Sensitivity Analysis - Calculated vs. Observed Heads - K_{PCS}=0.005 ft/d



RMS Residual = 17.97 ft
Mean Absolute Residual = 15.08 ft

Figure 4-5. Sensitivity Analysis - Calculated vs. Observed Heads - KPCS=0.02 ft/d

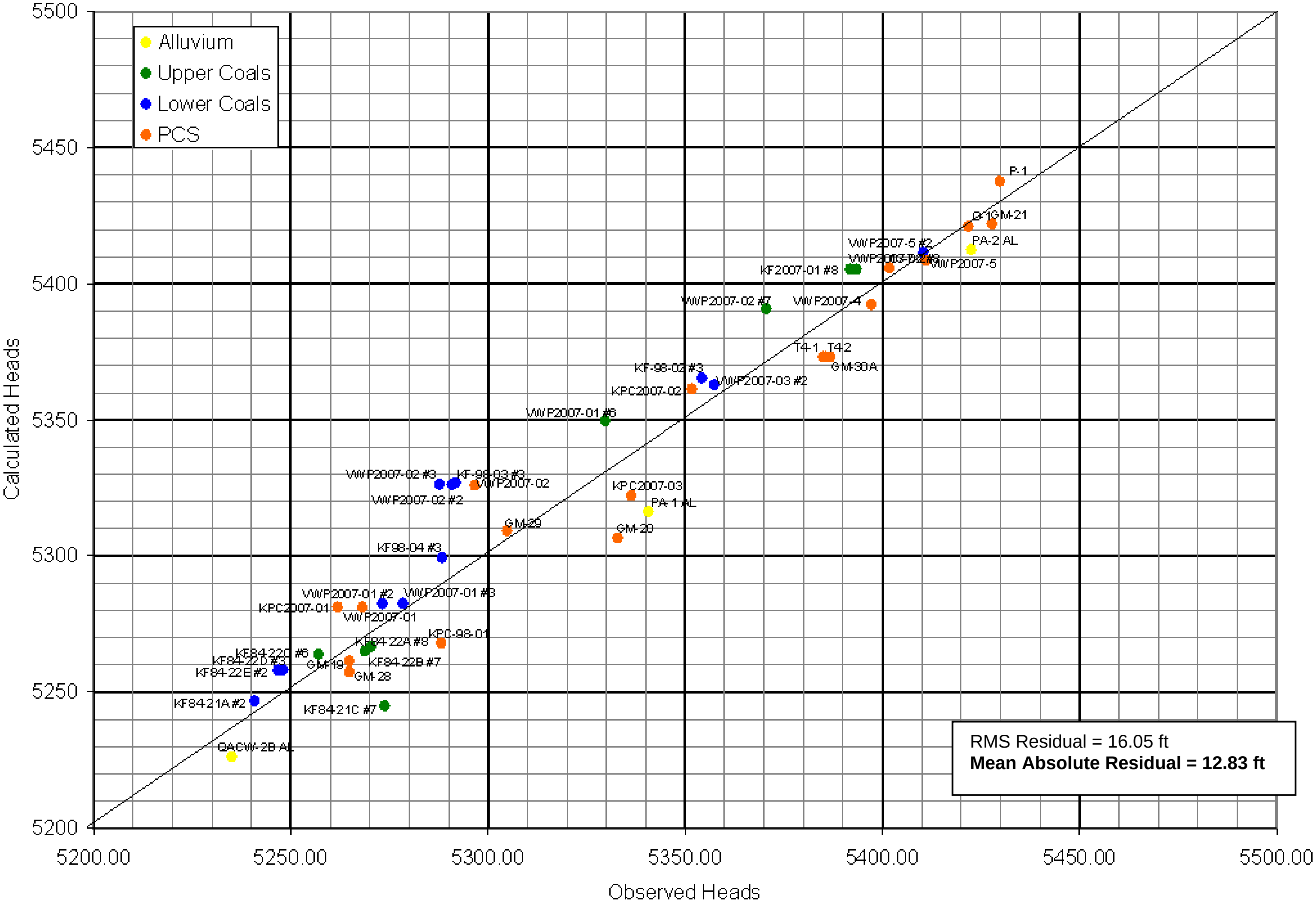
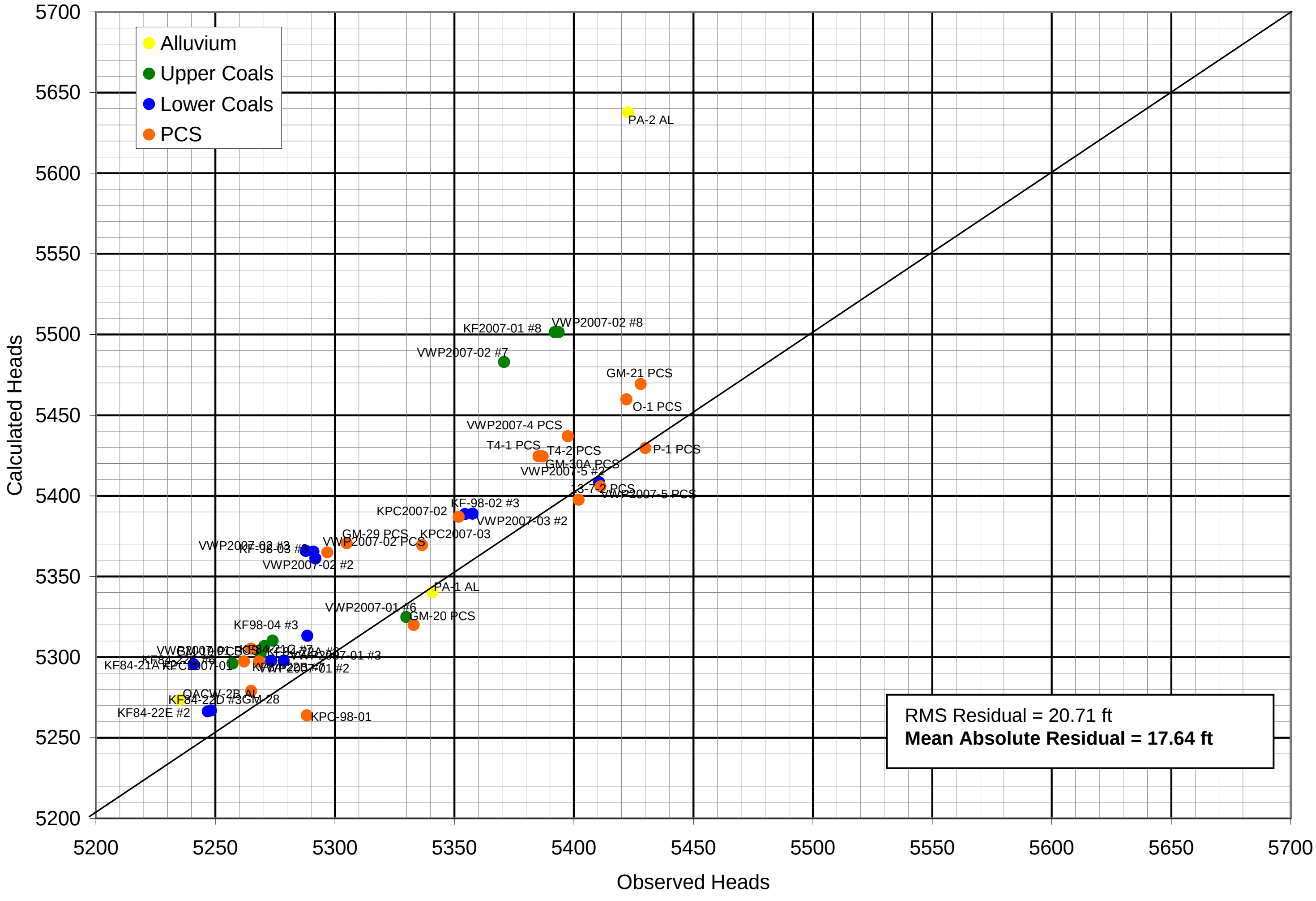


FIGURE 4-6. Sensitivity Analysis - Calculated vs. Observed Heads – Kx of upper coals X5



RMS Residual = 20.71 ft
Mean Absolute Residual = 17.64 ft

FIGURE 4-7. Sensitivity Analysis - Calculated vs. Observed Heads – Kx of upper coals /2

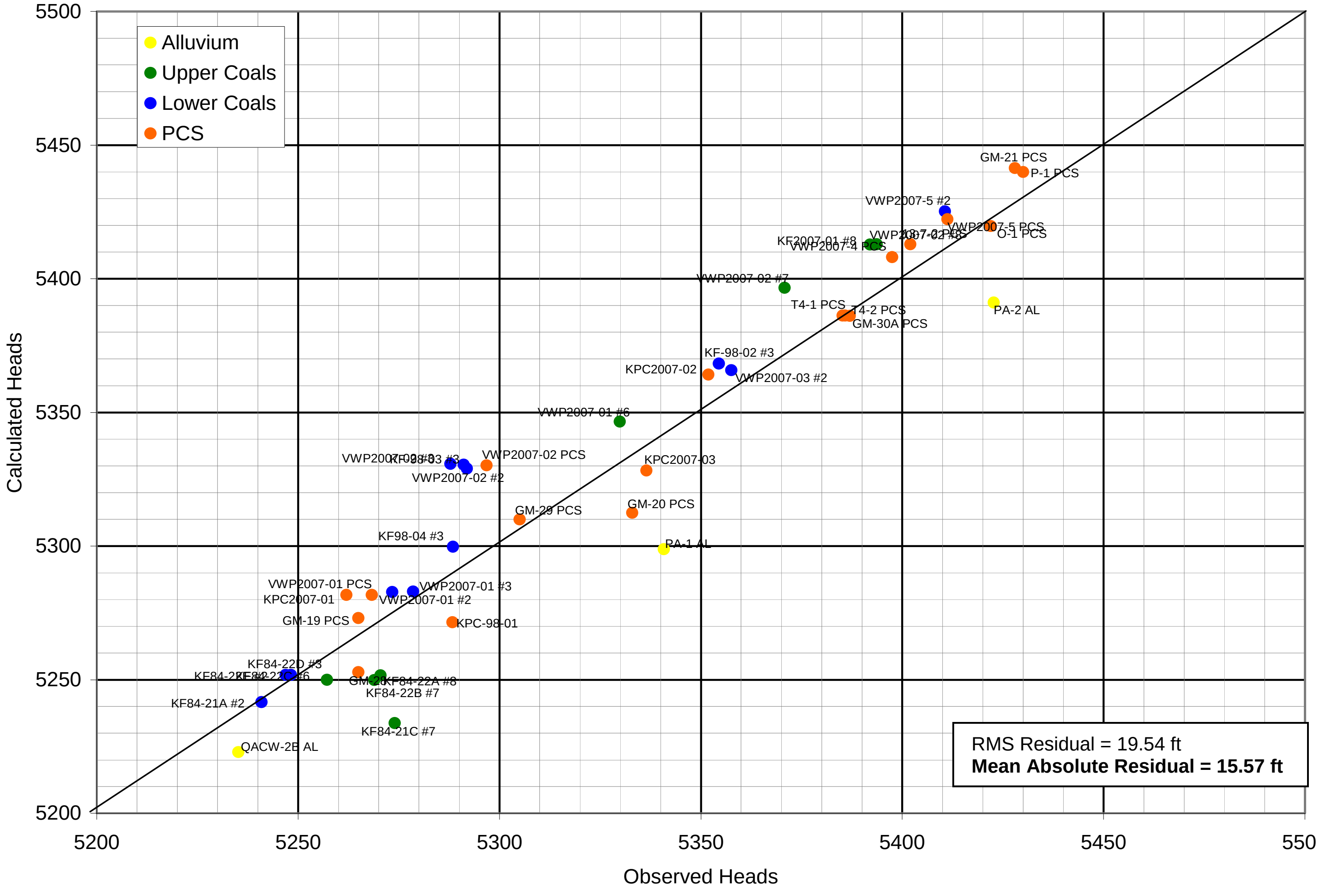
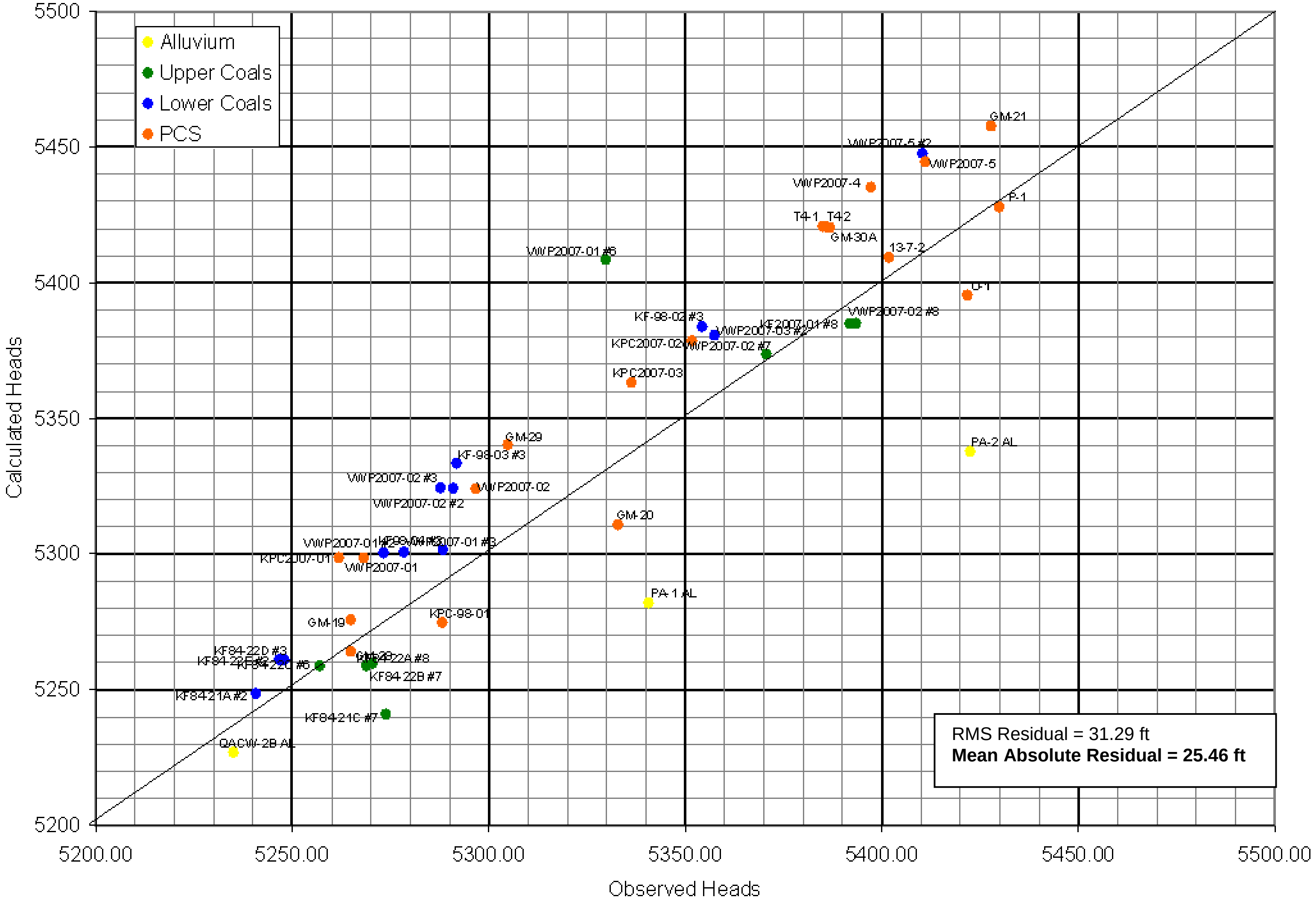


FIGURE 4-8. Sensitivity Analysis - Calculated vs. Observed Heads - $K_{\text{weathered coal}}=K_{\text{unweathered coal}}$



RMS Residual = 31.29 ft
Mean Absolute Residual = 25.46 ft

FIGURE 4-9. Sensitivity Analysis - Calculated vs. Observed Heads - Kz_{14}=5x10^{-6} ft/d (Kx/Kz=100)

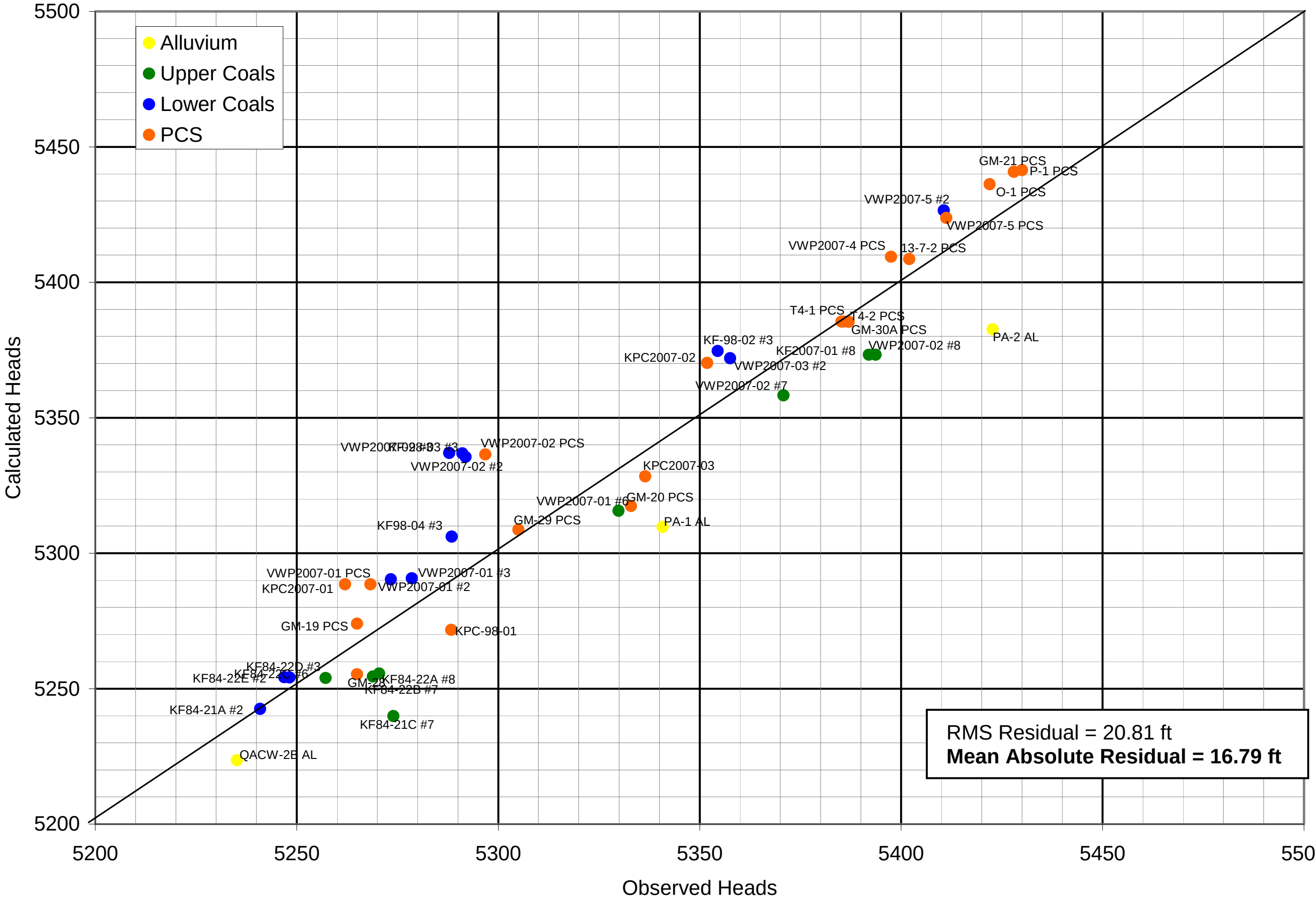
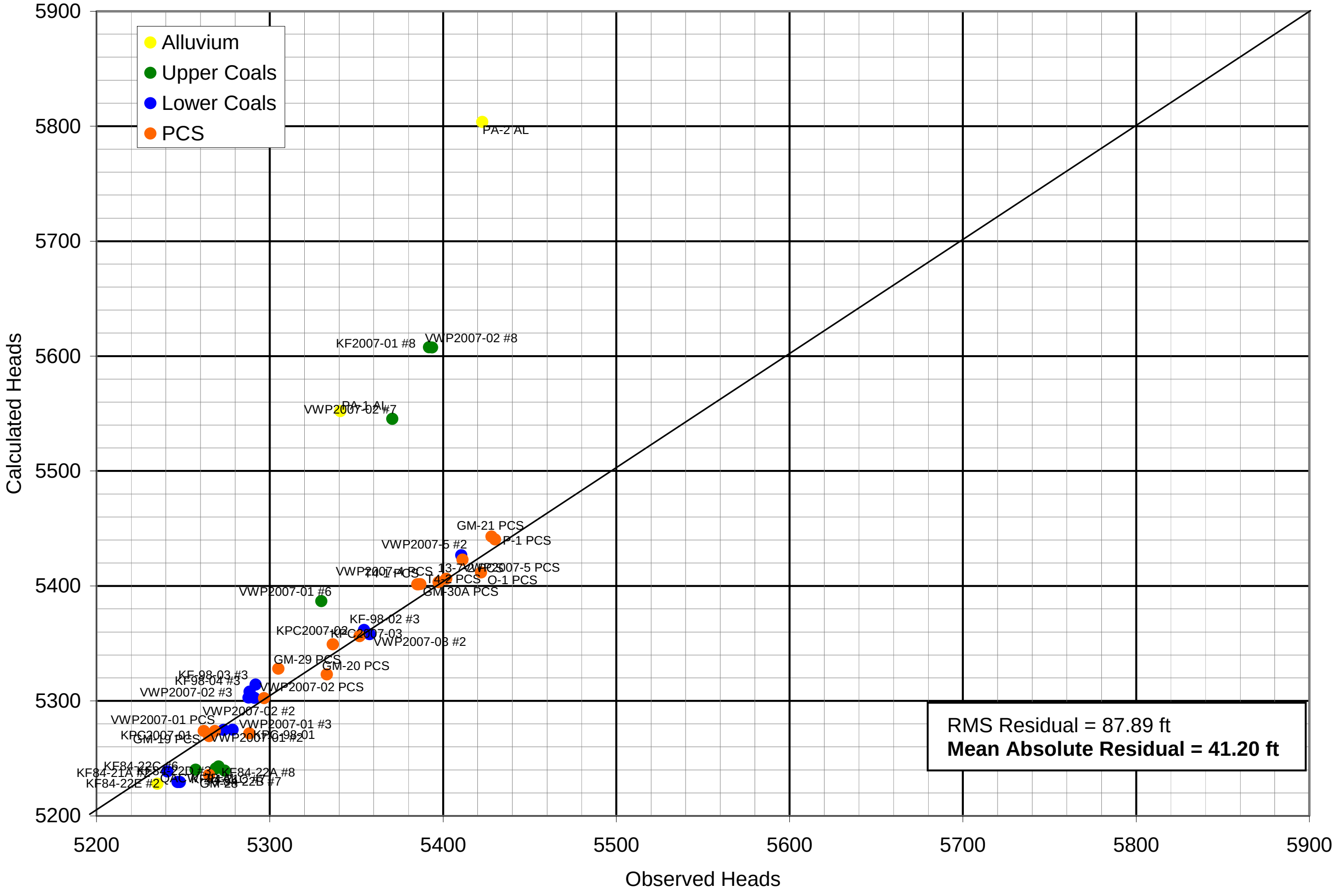


FIGURE 4-10. Sensitivity Analysis - Calculated vs. Observed Heads - Kz_{14}=5x10^{-7} ft/d (Kx/Kz=1,000)



RMS Residual = 87.89 ft

Mean Absolute Residual = 41.20 ft

FIGURE 4-11. Sensitivity Analysis - Calculated vs. Observed Heads - $Kz_{UpperIB}=2x10^{-7}$ ft/d (Kx/Kz=2,500)

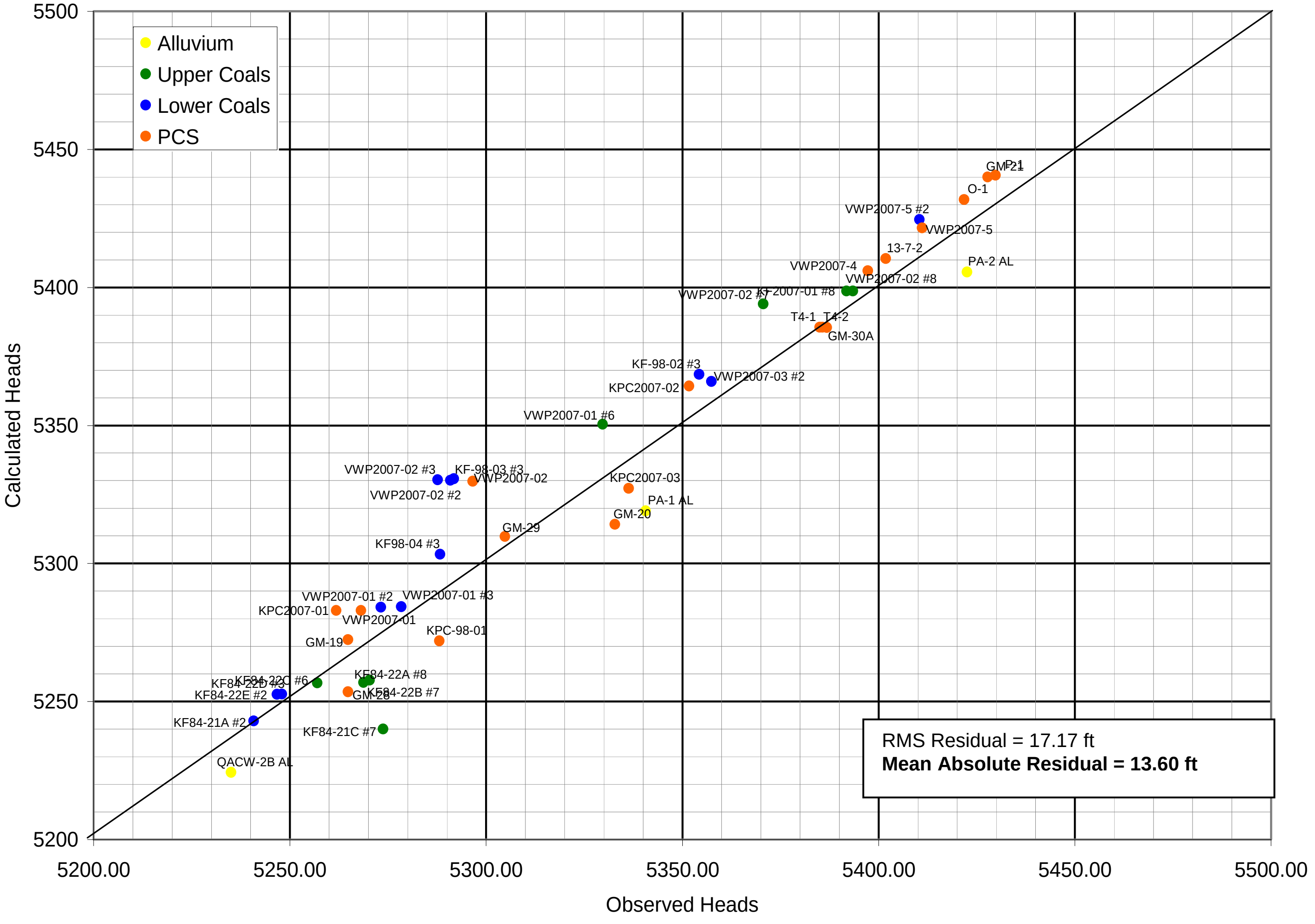


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FIGURE 4-12. Sensitivity Analysis - Calculated vs. Observed Heads - $Kz_{UpperIB}$=2.5x10^{-5} ft/d (Kx/Kz=20)

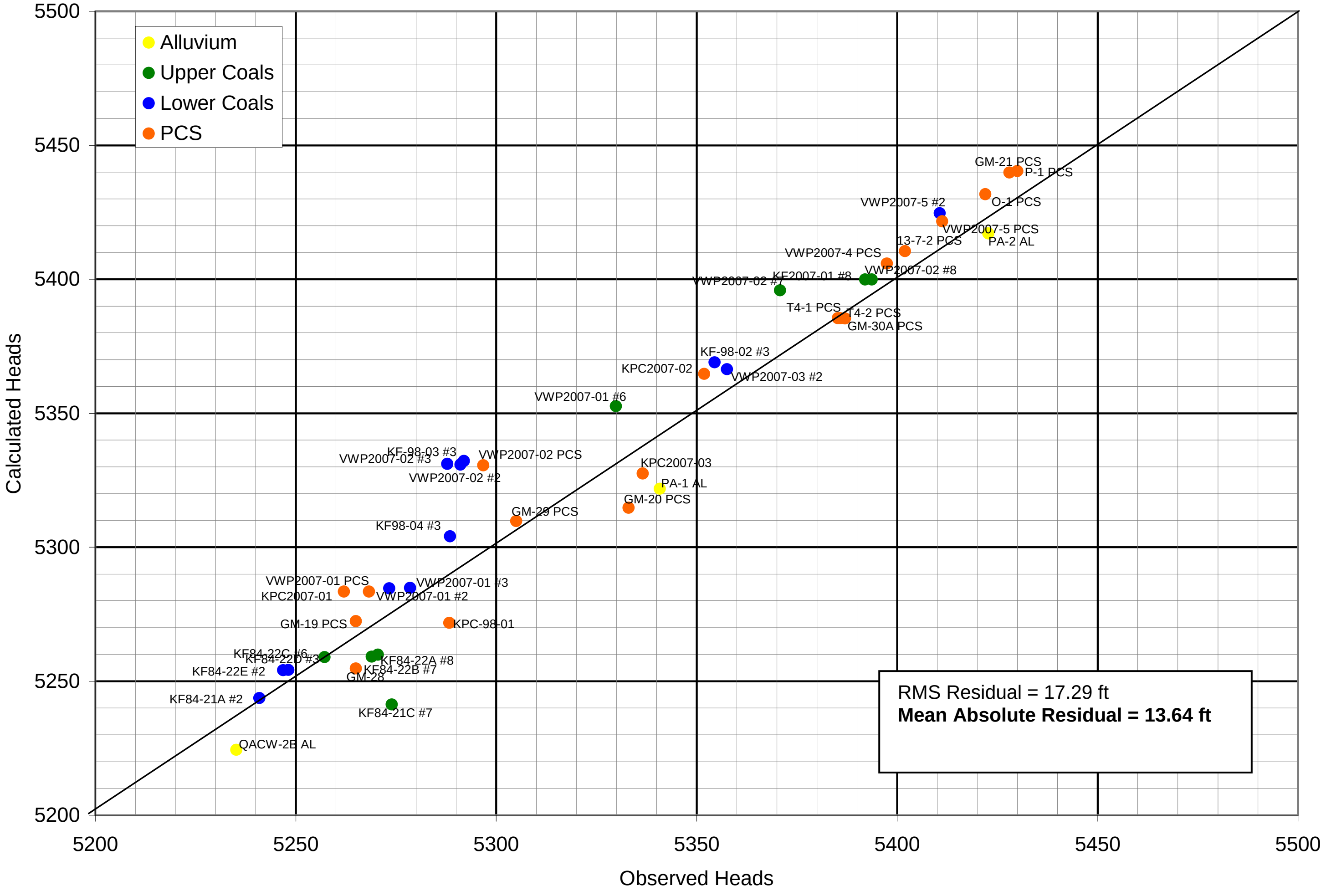


FIGURE 4-13. Sensitivity Analysis - Calculated vs. Observed Heads - $Kz_{LowerIB}$=2x10^{-7} ft/d (Kx/Kz=2,500)

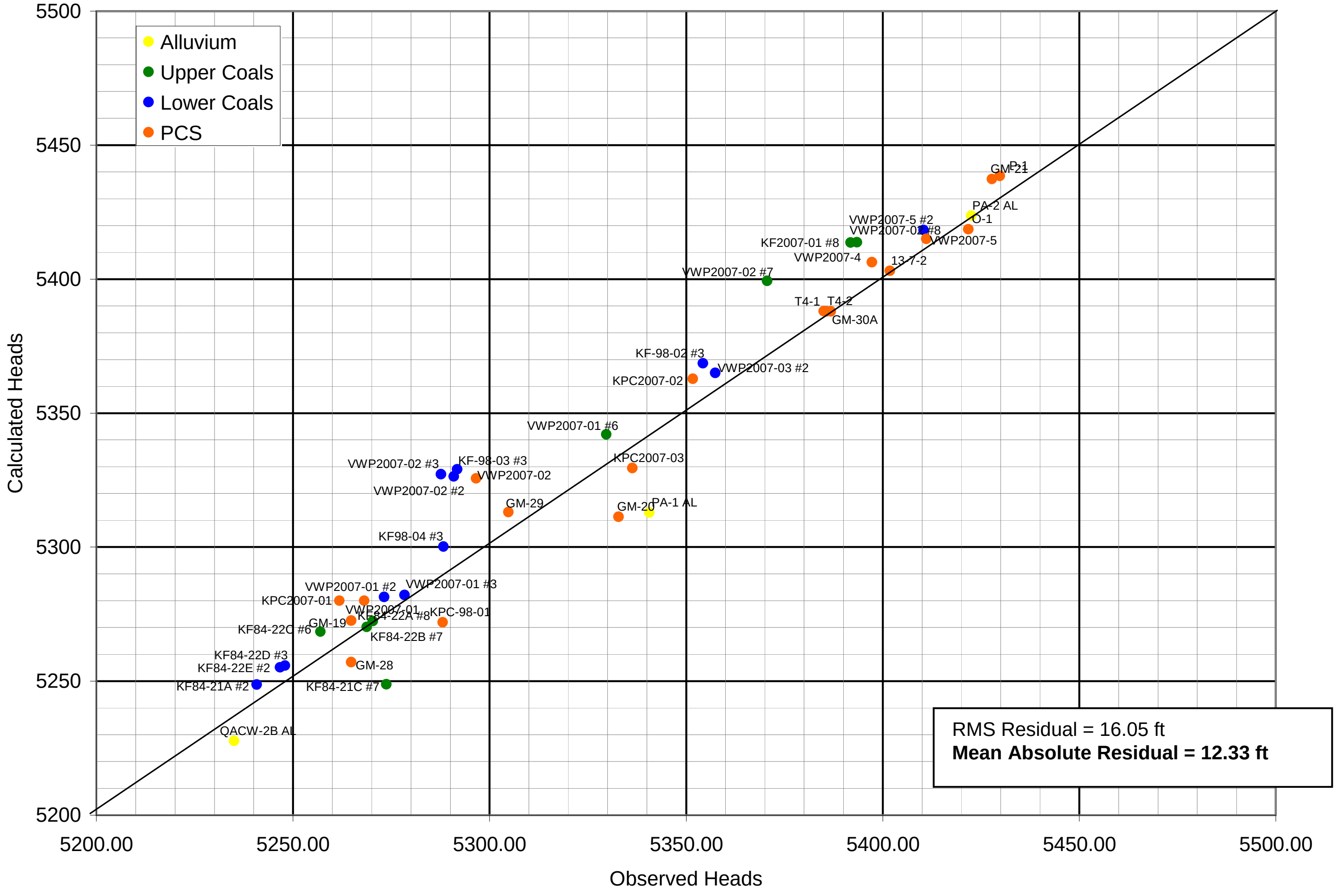


Figure 4-14. Sensitivity Analysis - Calculated vs. Observed Heads - K_{al}=31 ft/d

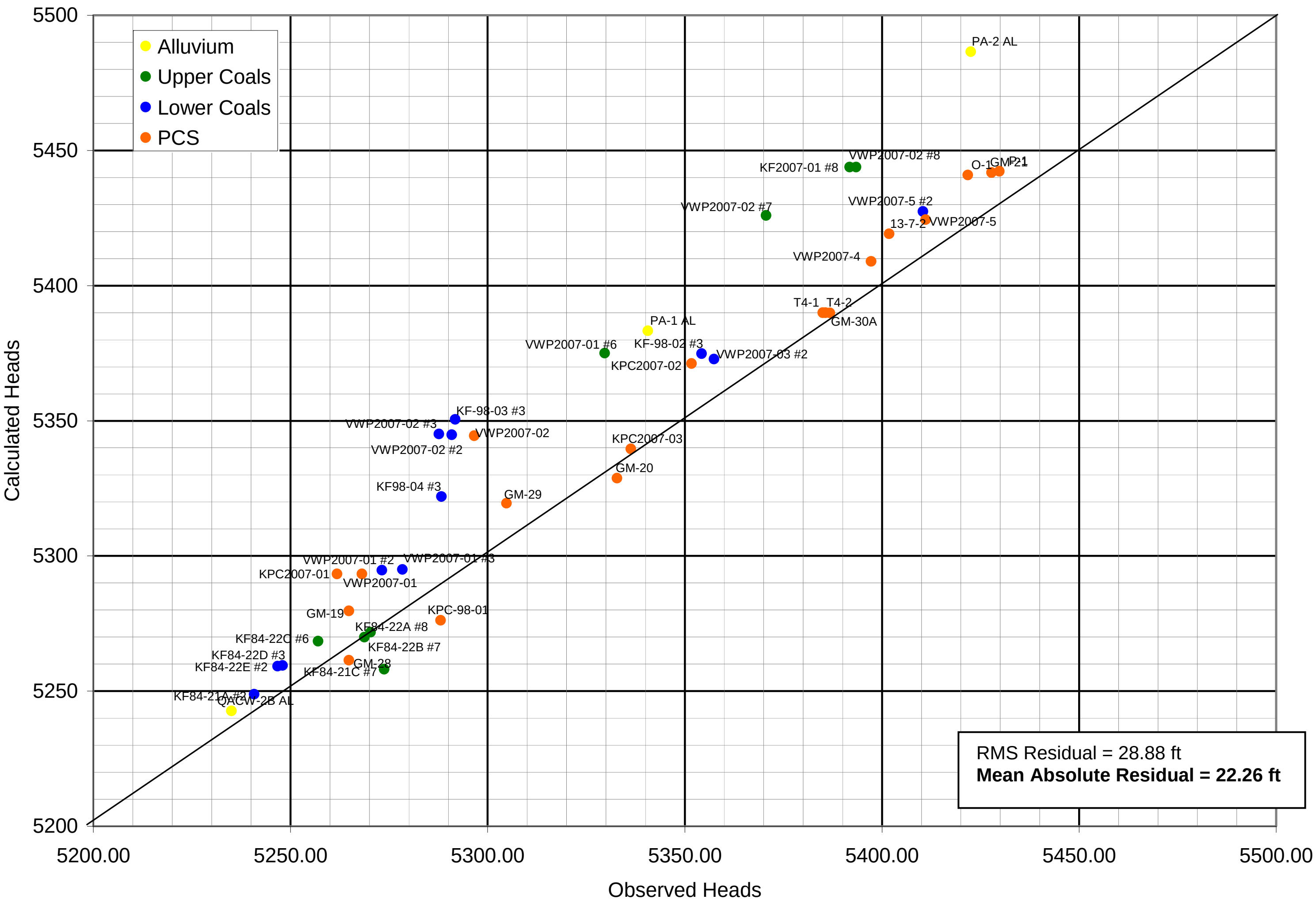
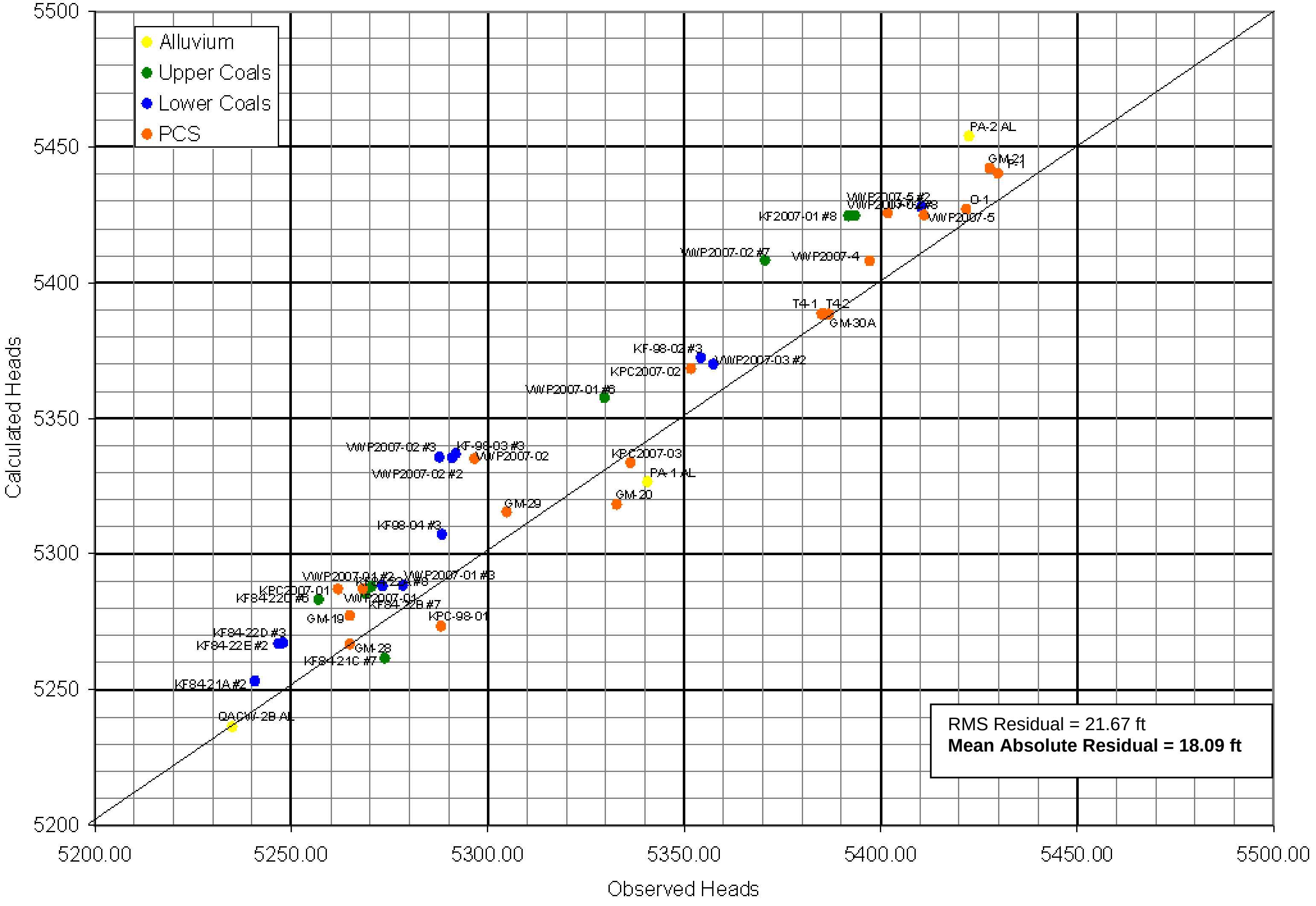
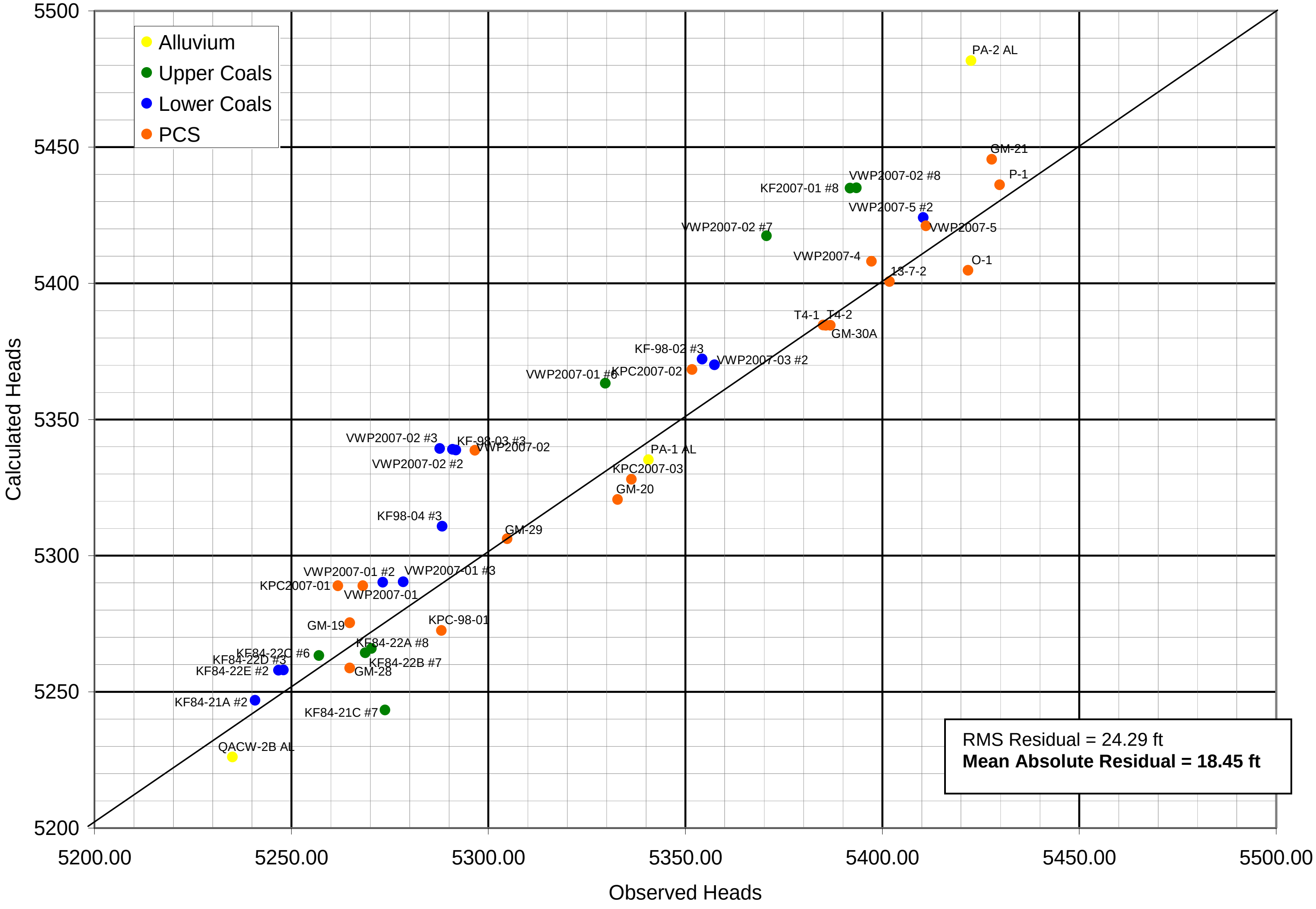


Figure 4-15. Sensitivity Analysis - Calculated vs. Observed Heads - K_{al}=62 ft/d



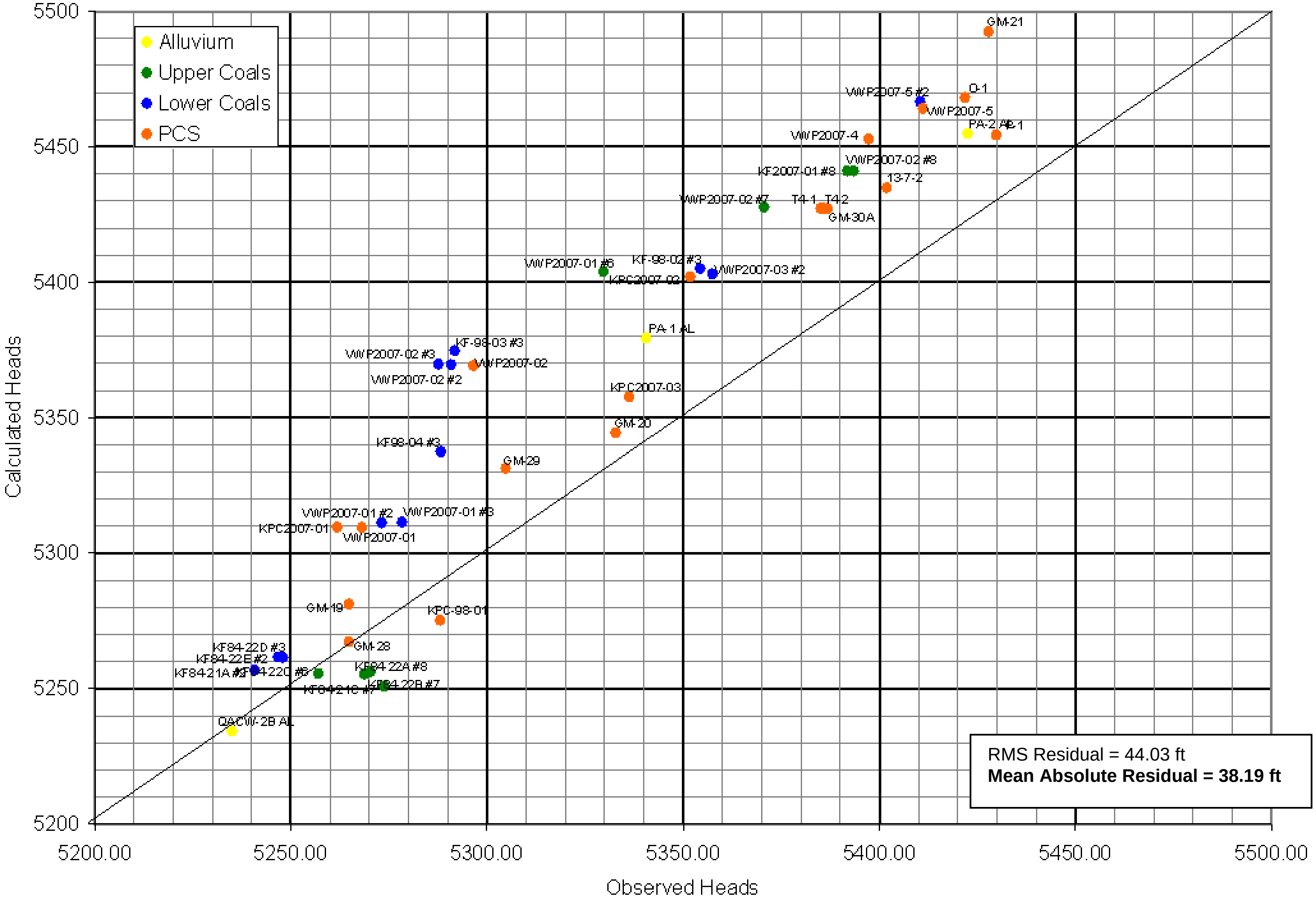
RMS Residual = 21.67 ft
Mean Absolute Residual = 18.09 ft

Figure 4-16. Sensitivity Analysis - Calculated vs. Observed Heads - K_{al}=187 ft/d



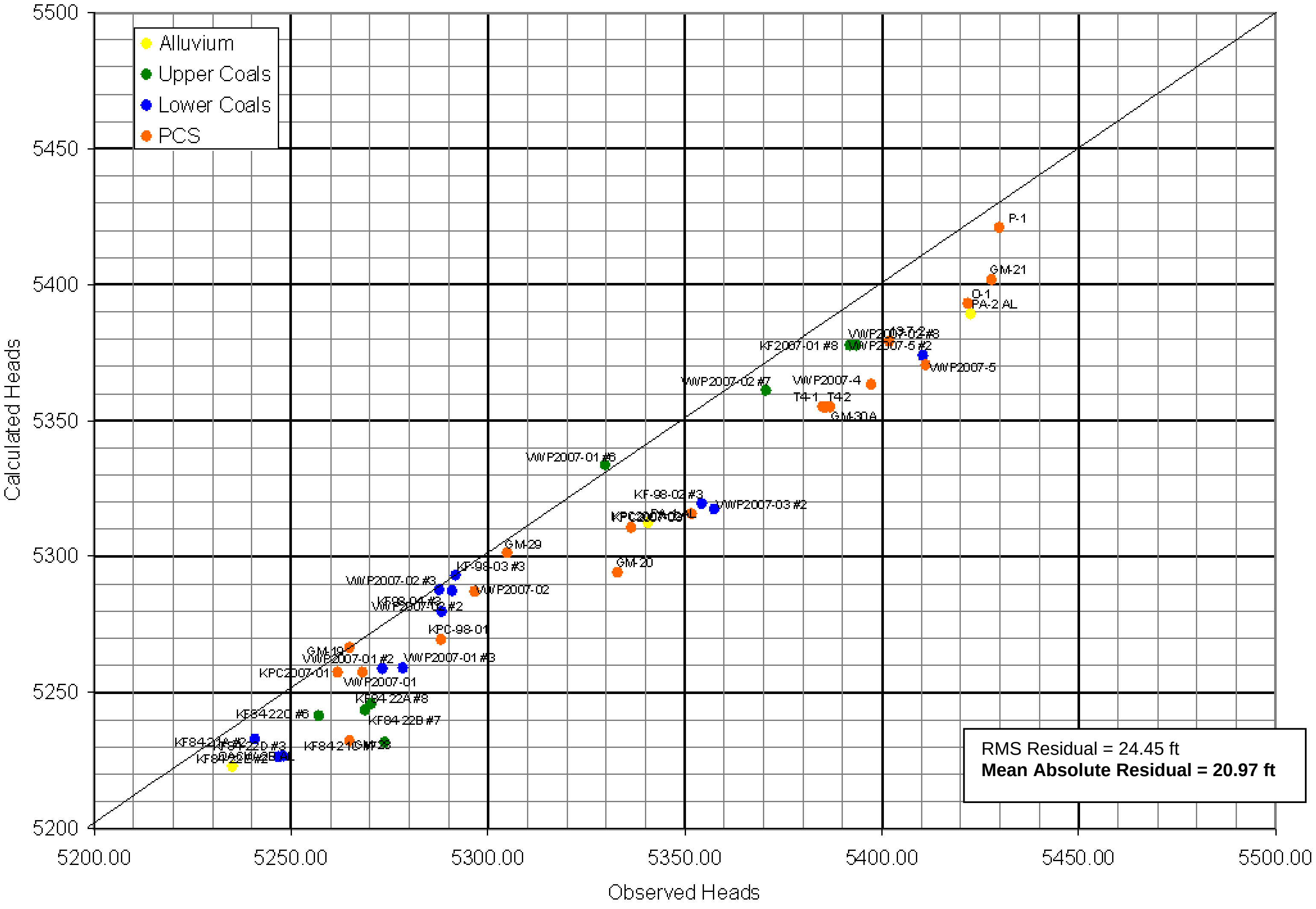
RMS Residual = 24.29 ft
Mean Absolute Residual = 18.45 ft

Figure 4-17. Sensitivity Analysis - Calculated vs. Observed Heads - Leakage Coefficient = 1/2 Calibrated Value



RMS Residual = 44.03 ft
Mean Absolute Residual = 38.19 ft

Figure 4-18. Sensitivity Analysis - Calculated vs. Observed Heads - Leakage Coefficient = 2x Calibrated Value



RMS Residual = 24.45 ft

Mean Absolute Residual = 20.97 ft

Figure 4-19. Sensitivity Analysis - Calculated vs. Observed Heads - Leakage Coefficient=3x10^{-4}/d

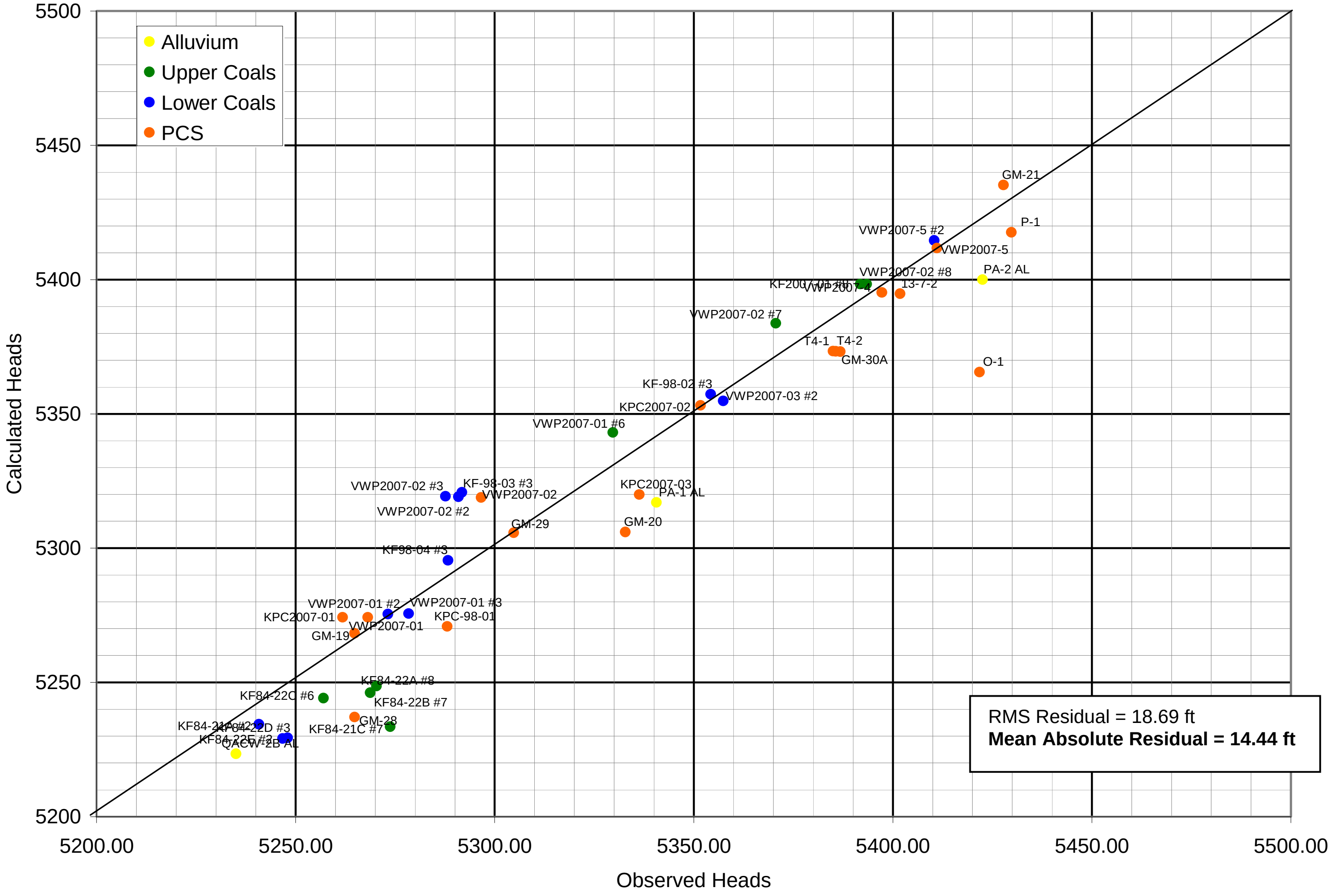
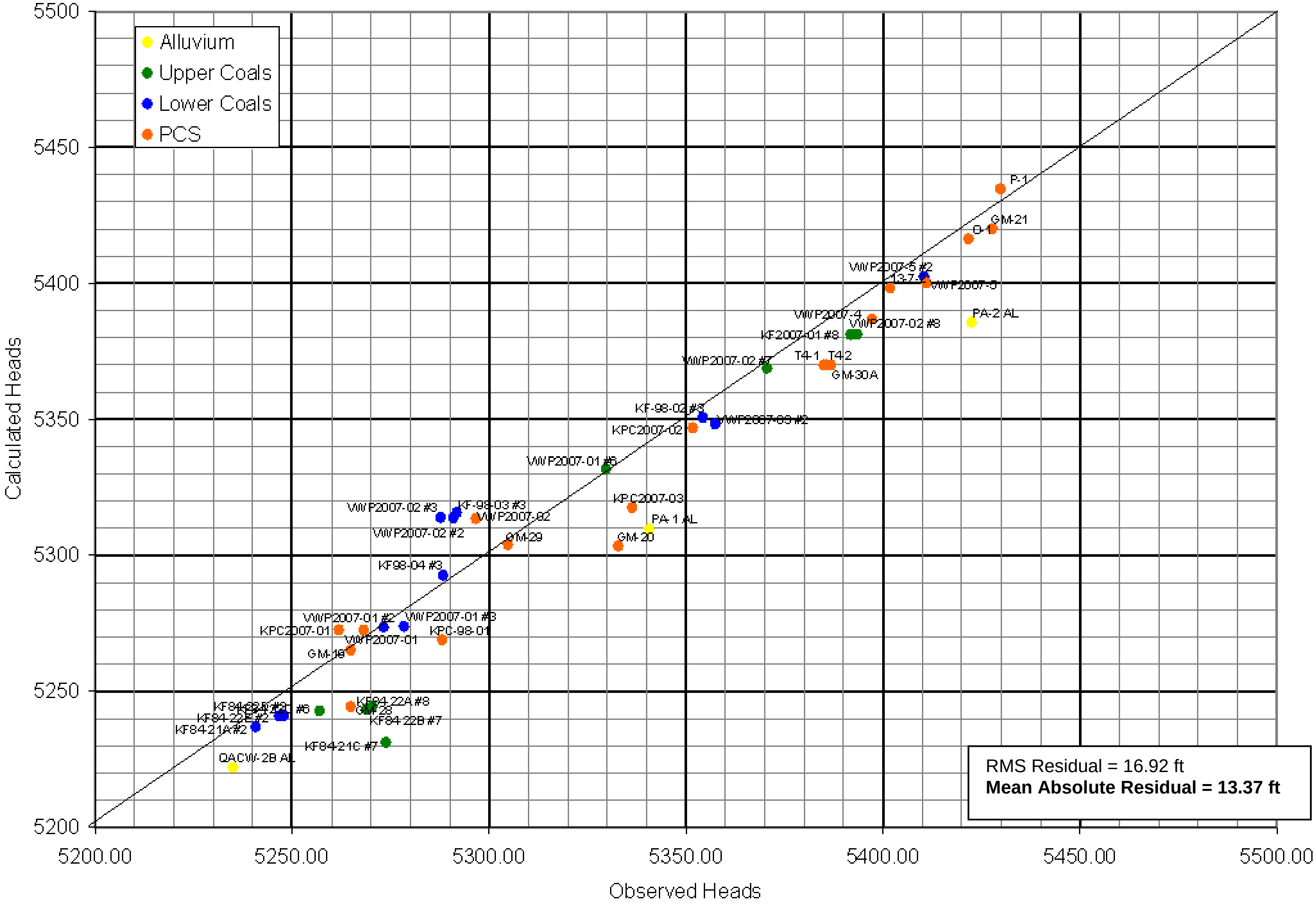


Figure 4-20. Sensitivity Analysis - Calculated vs. Observed Heads - Recharge = 0.8 x Calibrated Value



RMS Residual = 16.92 ft
Mean Absolute Residual = 13.37 ft

Figure 4-21. Sensitivity Analysis - Calculated vs. Observed Heads - Recharge = 1.2 x Calibrated Value

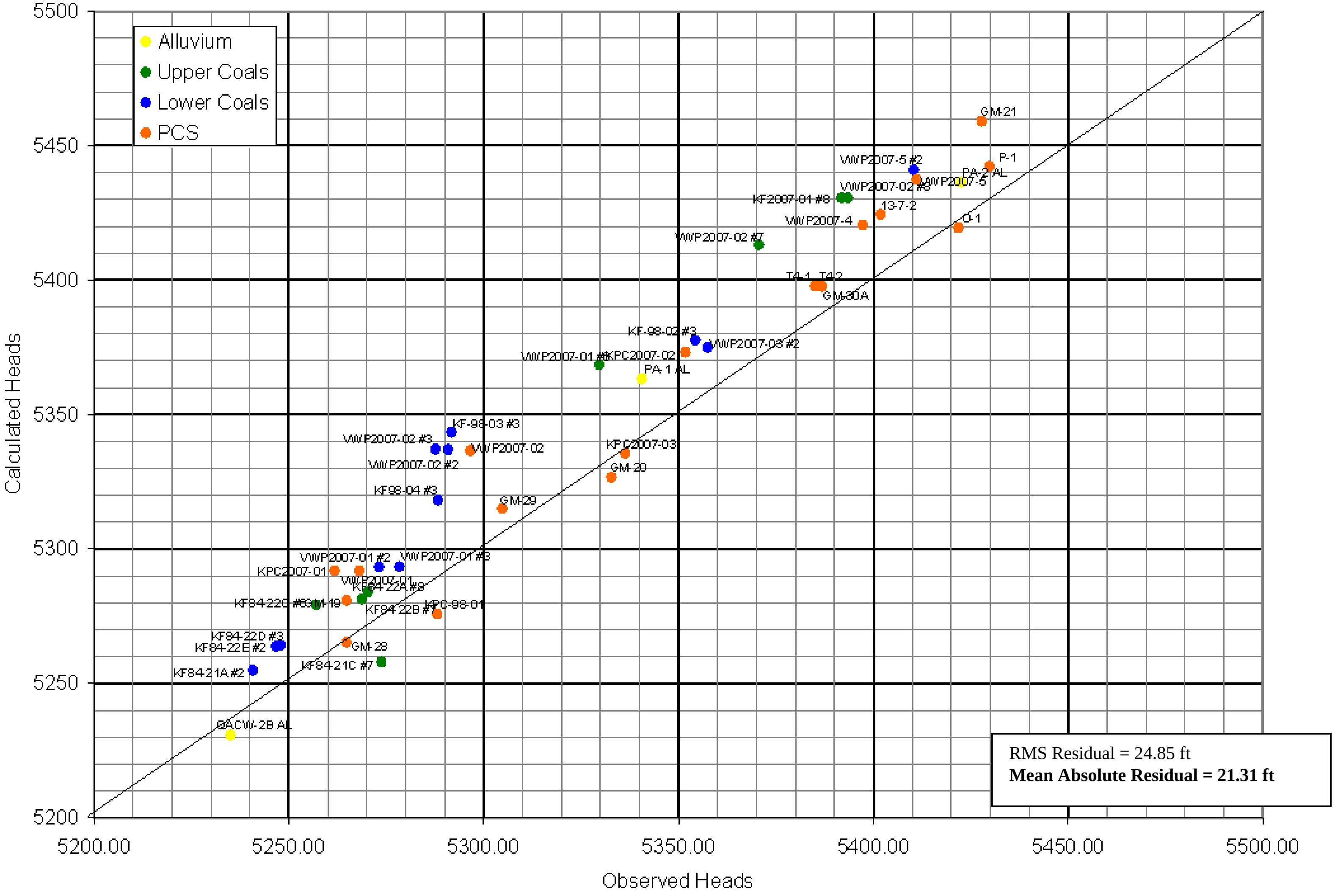


Figure 4-22. Drawdown and Recovery-Sensitivity Results Default Ss versus Base Ss

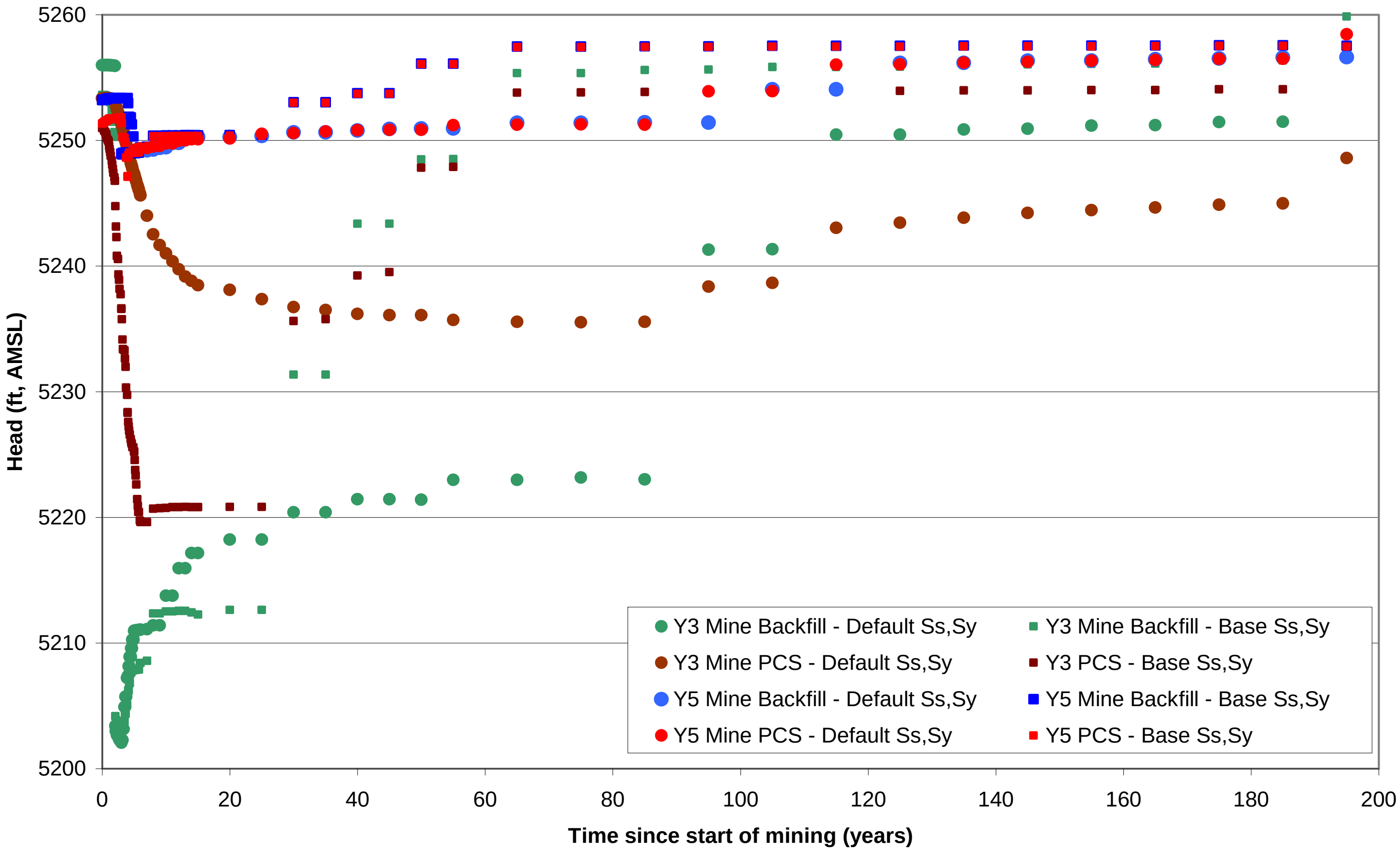


Figure 4-23. Maximum 5-foot Drawdown in No. 8 Coal –Sensitivity Results Default Ss, Sy versus Model Ss, Sy

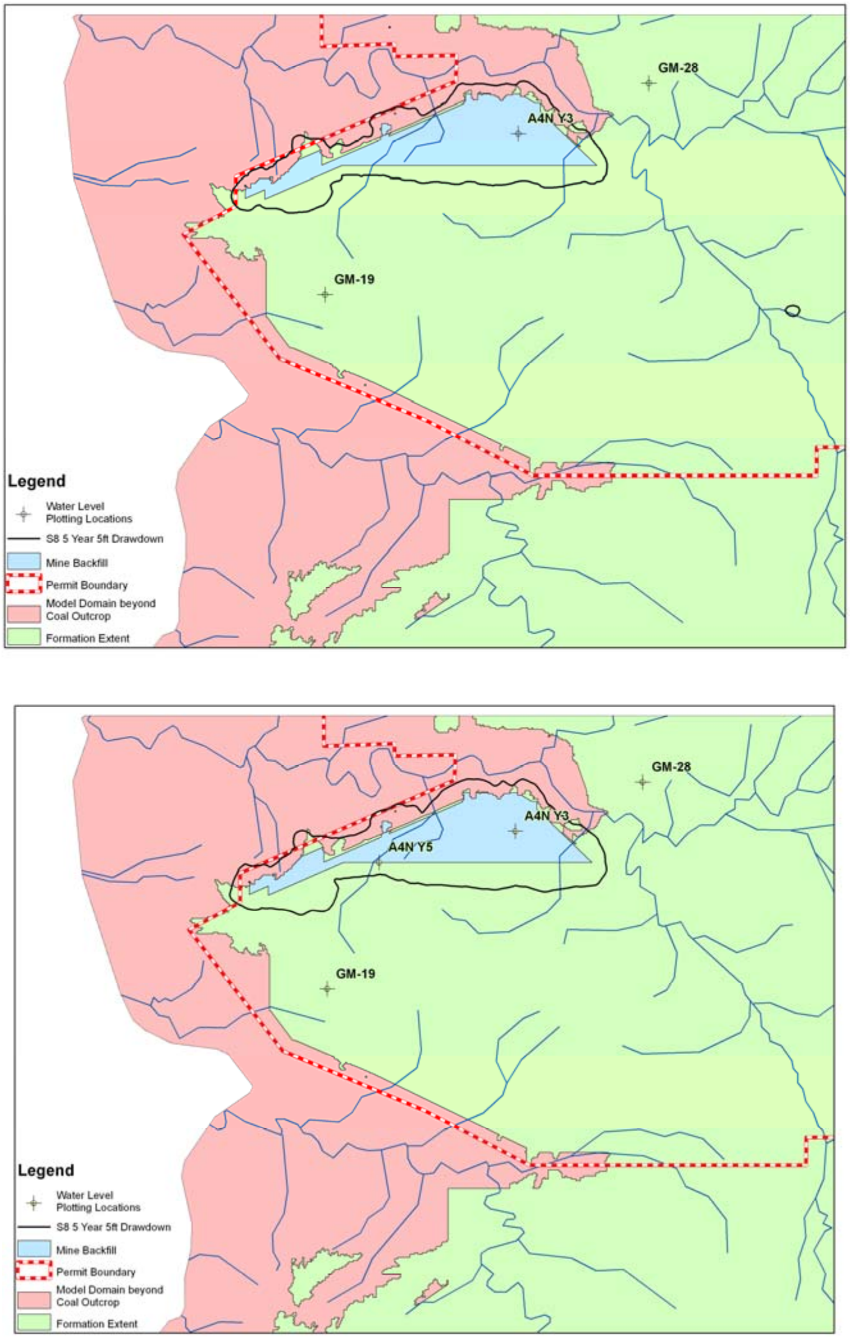


Figure 4-24. Maximum 5-foot Drawdown in No. 3 Coal –Sensitivity Results Default Ss versus Model Ss

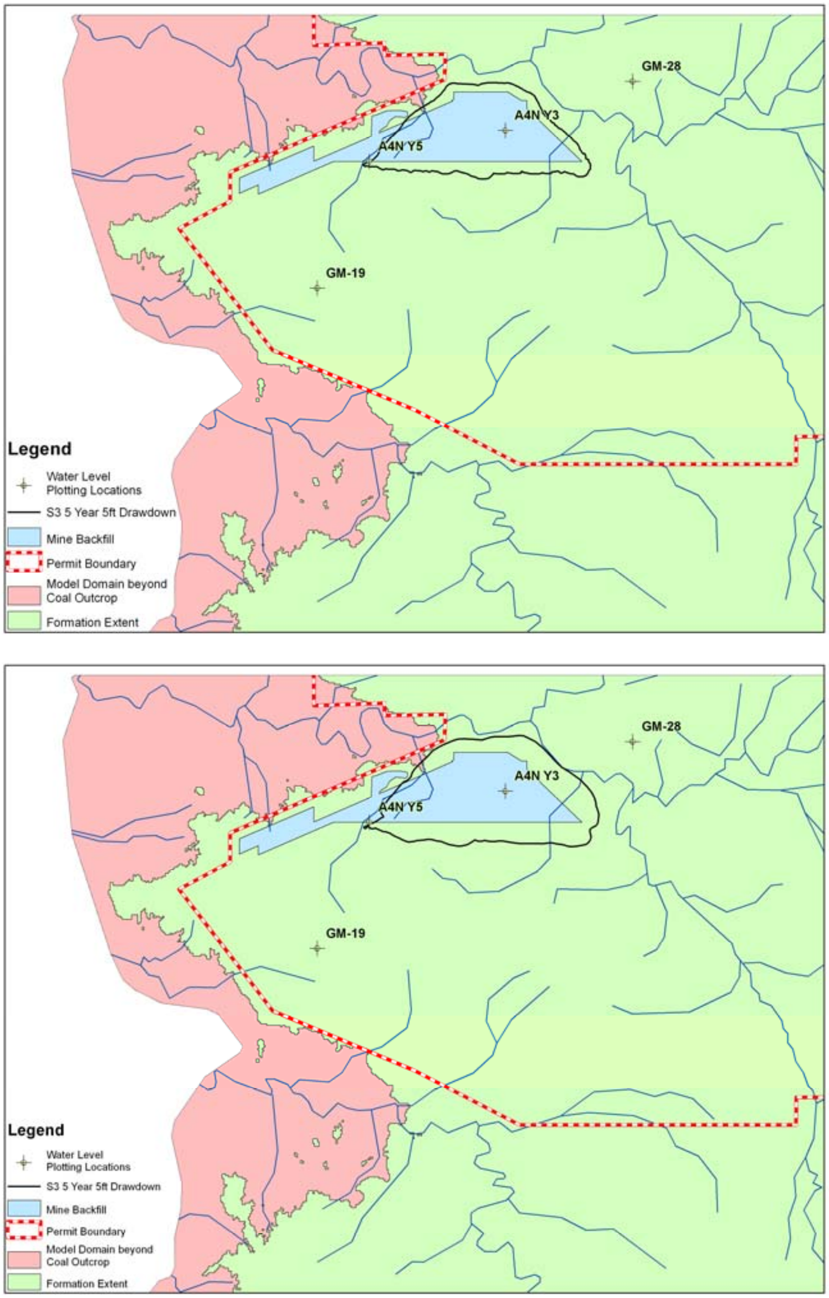
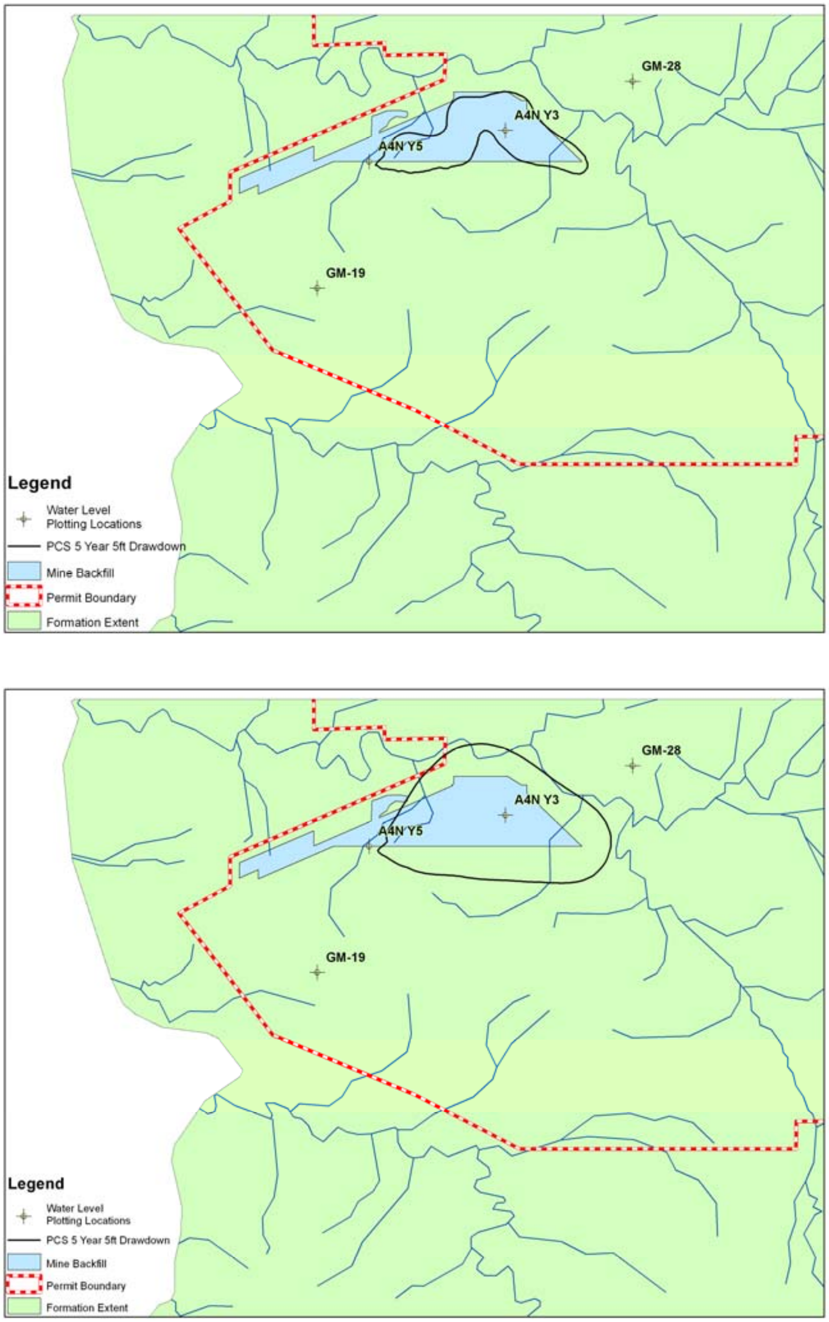


Figure 4-25. Maximum 5-foot Drawdown in PCS –Sensitivity Results Default Ss versus Model Ss



ATTACHMENT 1

HYDRAULIC CONDUCTIVITY AND STORAGE CHARACTERISTICS OF MODELED HYDROGEOLOGIC UNITS

Pinabete and Cottonwood Alluvium

The estimated range in hydraulic conductivities for the alluvial fill deposits within the valley bottoms of Cottonwood and Pinabete Arroyos within the model domain were obtained from constant rate pumping tests performed on wells PA-1 and PA-2 completed in Pinabete Alluvium within Area IV South on May 16, 1998. The test results are summarized in Table 6.G-4 in Appendix 6.G of the Navajo Mine permit application package (BNCC, 2011). These results indicate a hydraulic conductivity of 51.3 ft/day (1.8 x10-2 cm/sec) for well PA-1 and a hydraulic conductivity of 11.5 ft/day (4.1 x10-3 cm/sec) for well PA-2. Tests were not conducted on wells in Cottonwood Arroyo because wells were dry or had limited saturation insufficient for aquifer testing. However, the hydraulic conductivities for the Cottonwood Alluvium should be similar to that alluvial deposits along Pinabete Arroyo because the alluvial materials in the two arroyos are similar, ranging from fine-grained wind blown sand to coarse-grained sands and gravels.

Kernodele (1996) notes that the specific yield for the alluvium in the San Juan Basin would be in the range from 0.1 to 0.25 and that tests for specific storage have been performed because the alluvium is unconfined. The FEFLOW default specific yield of 0.2 is within the range indicated by Kernodele and has been used to represent the alluvium in the transient simulations. Physically, specific storage is a measure of the compressibility of the aquifer matrix and the expansion of water. In unconfined aquifers, changes in storage are controlled by the specific yield and not by the compressibility of the matrix or the water in storage.

Pictured Cliffs Sandstone

The hydraulic conductivities for the Pictured Cliffs Sandstone (PCS) from aquifer tests performed within the model domain are summarized in Table 6.G-11 in Appendix 6.G of the Navajo Mine permit application package (BNCC, 2011). Well KPC-98-01 was installed in 1998 near the PCS outcrop at the location west of Navajo Mine lease Area IV South. In 2007, wells KPC2007-01, KPC2007-02, and KPC2007-03 were completed in the PCS at locations around the perimeter of Area IV South. Water yields from these monitoring wells completed in the PCS at the Navajo Mine lease are quite low. Two of the PCS wells were quickly pumped or bailed dry during conventional sampling. The yield from one of the PCS wells was sufficient to sustain a rate of about 0.4 gallons per minute (gpm) during a constant rate pumping test. The fourth PCS monitoring well was pumped dry after about 140 minutes during a constant-rate pumping test at a rate of about 1 gpm.

An aquifer test was conducted by Science Application Inc. (1979) at well T4-1 installed in the PCS near the western side of the Navajo Mine Area V lease. The drawdown and recovery measurements were recorded at the pumped well, at observation well GM30A located 55.8 ft from the pumping well, and at observation well T4-2 located 12.5 ft from the pumping well. The top of the PCS is approximately 146 ft blow ground surface at the test location while the static water level was at a depth of 134 ft, demonstrating confined conditions at the test location. The results of this aquifer test are summarized in the attached table, along with the results of tests performed at the PCS monitoring wells installed within or adjacent to Area IV South.

The hydraulic conductivity from the recovery response at well GM-30A from the pumping test at the PCS well T4-1 was 0.0016 ft/day (5.6 x 10^{-7} cm/sec). The storage coefficient determined from the observation well response at GM-30A was 3.4 x 10^{-4}. A specific storage of 3.9 x 10^{-6} per foot is estimated based on the estimated PCS aquifer thickness of 84 feet at the test well location. The hydraulic conductivity estimate for the PCS of 0.02 ft/day (7.0 x 10^{-6} cm/sec) was obtained from the test at monitoring well KPC-98-01, located west of the Navajo Mine Area IV South coal lease. The PCS is unconfined at this location. The results for this well are consistent with the aquifer test results of 0.032 ft/day (1.1 x 10^{-5} cm/sec) from a slug test at Well O-1 completed in the PCS at the Burnham Mine but higher than the range from 0.0 to 0.0001 ft/day (2.6 x 10^{-6} to 3.5 10^{-8} cm/sec) obtained from the slug tests at the three other PCS monitoring wells at the Navajo Mine as summarized in the attached.

Pumping test results for the PCS monitoring well O-1 in the PAP for the Burnham Mine are on file in the library of the OSM in Denver. In this well test, pumping at a relatively high rate of 18.3 gpm could be sustained for only 8.7 minutes when most of the well-bore storage water was removed and the test had to be terminated. Although the results were interpreted in the Burnham Mine PAP as a pumping test, this approach is not correct due to the predominant influence of well-bore storage. Consequently, the well test results have been reinterpreted as a slug test in the attached table. Slug test results indicate a hydraulic conductivity of 0.032 ft/day (1.1 x 10^{-5} cm/sec).

There is no information in the literature concerning the specific yield for the PCS and little information concerning specific yield of sandstone aquifers. The specific yield is the storage parameter that applies only to the unconfined portion of the aquifer. Normally this is where the aquifer is shallow and often weathered. Johnson (1967) provides specific yield values ranging from about 0.1 to 0.3 for fine sands and sands. The New Mexico State Engineer (2010) provides specific yield estimates of 0.14 and 0.25 for well tests in the Mesa Verde Group. The Mesa Verde Group is comprised of inter bedded sedimentary deposits of sandstones, siltstones, shales and coals not unlike the Fruitland Formation and the PCS. Consequently, the FEFLOW default specific yield of 0.2 is within the range indicated by the Mesa Verde tests and has been used to represent both the PCS and the interburden and overburden sedimentary layers in the Fruitland Formation.

Summary of Pictured Cliffs Sandstone Aquifer Test Results

Well	Well Depth (ft)	Test type	Transmissivity (ft^2/day)	Hydraulic conductivity		Saturated thickness (ft)	Storage coefficient
				(ft/day)	(cm/sec)		
KPC-98-01	125.7	0.4 gpm pumping test	0.79	0.020	7.1E-06	39	NA
KPC2007-01	208.84	0.95 gpm, Theis analysis	0.576	0.0074	2.6E-06	78	NA
KPC2007-03	138.4	Bower and Rice	0.04	0.004	1.4E-06	10	NA
		Horslev slug test	0.9	0.09	3.2E-05	10	NA
Pumping test well T4-1	228	0.15 gpm pumping	0.1203	0.0014	4.9E-07	84	0.00032
Recovery test well GM-30A	191.6	Theis recovery	0.1337	0.0016	5.6E-07	84	0.00034
O-1[1]	414	Cooper slug test	2.7300	0.0321	1.1E-05	85	NA
		Horslev slug test	3.7500	0.0441	1.6E-05	85	NA

[1] Burnham Mine well pumped dry in 8.7 minutes at 18.3 gpm. Re-interpreted as a slug test

Fruitland Coals

The hydraulic conductivities for the Fruitland Formation coal zones have been obtained from aquifer tests performed within the model domain as summarized in Table 6.G-8 in Appendix 6.G of the Navajo Mine permit application package (BNCC, 2011) and from tests performed at Fruitland coal wells at Navajo Mine as summarized in Table 6-1 in the Navajo Mine permit application package (BNCC, 2011). The results of these aquifer tests are summarized in the attached table, including a description of the relevant coal unit tested. The upper coal units, #8 and #7 have higher hydraulic conductivities than the lower coal units. Test information is sufficient to establish a range for the hydraulic conductivities for the No. 8 coal, the No. 7 coal, and the No. 3 coal. Only one test result was found for the No. 6 coal, the No. 4 coal, and the No. 2 coal. These tests were within the range found for the No. 3 coal. Thus the range of hydraulic conductivity for the No. 3 coal is also used for all the lower coal seams. All of these tests were single well tests, which do not provide estimates of confined storage coefficients for the coals.

A storage coefficient estimate of 4.2 x 10^{-4} was reported in the Western Coal Company (1979) permit application for the San Juan Underground Mine Project. The thickness of the coal zone tested and the specific storage were not listed. However, the thickness of No. 8 coal unit at San Juan Mine averages about 15 feet, resulting in an approximate specific storage value of 2.8 x 10^{-5} per foot. A storage coefficient estimate of 1 x 10^{-5} was also obtained by Neimczyk and Walters (1980) using a single well step-test of Fruitland coal well GT-2 located east of the San Juan Mine. Based on an estimated 14.3 feet of coal in the test well, the specific storage of the coal is approximately of 3.9 x 10^{-6} per foot. The specific storage estimates determined from these tests for the Fruitland No. 8 coal are within the range of 1 x 10^{-3} to 3 x 10^{-7} per foot determined from fourteen pump tests of coal referenced by Rehm et al (1980). The average specific storage from these fourteen tests was 3 x 10^{-5} per foot, which is almost the same as the estimate for the No. 8 coal reported for the San Juan Underground Mine Project.

A lower specific yield of 0.5 % is used for the coals due to the low effective porosity of the coals. This specific yield value is consistent with the median value of 0.4% for coal was found in a comprehensive review of aquifer characteristics from pumping tests conducted in support of plans for coal mining and reclamation in the Powder River Basin (Applied Hydrology Associates and Greystone Environmental Consultants (2002).

Fruitland Overburden and Interburden

Laboratory tests of two samples of unconsolidated overburden material at the Navajo Mine found hydraulic conductivity values of 1.43 x 10^{-3} ft/day (5 x 10^{-7} cm/sec) and 9.64 x 10^{-4} ft/day (3.4 x 10^{-7} cm/sec). Frenzel and Lyford (1982) utilized literature estimates based on descriptions of the geology to estimate the horizontal hydraulic conductivity values for confining beds ranging from 8.64 x 10^{-3} ft/day to 8.64 x 10^{-4} ft/day. Vertical hydraulic conductivity values for the confining beds were estimated from model calibration and ranged from 5 x 10^{-6} ft/day to 8.64 x 10^{-8} ft/day and were generally 10^{-4} times lower than the horizontal hydraulic conductivities. Model calibration was very sensitive to the ratio.

Summary of Aquifer Test Results For Fruitland Coals

Well	Coal seam	Elevation (ft)	Well depth (ft)	Test type	Transmissivity (ft^2/day)	Hydraulic conductivity		Saturated thickness
						(ft/day)	(cm/sec)	
Kf-98-02	#3	5505.89	216.5	Displacement Test	0.0010	0.0001	4.6E-08	7.5
Kf-98-03	#3	5423.45	133.9	Bailed Recovery Test	0.010	0.002	7.1E-07	5
Kf-98-04	#3	5351.80	64.8	Bailed Recovery Test	0.010	0.001	3.5E-07	10
Kf84-22D	#3	5124.20	220	MCWhorter Recovery	0.01	0.002	7.1E-07	5.0
Kpc2007-01	#8	5352.97	118	Papadopulos-Cooper Pumping Test	1.398	0.056	2.0E-05	25
SJKF84#3	#8	4990.18	120	MCWhorter Recovery	0.71	0.04	1.4E-05	18.0
SJKF84#4	#8	5046.67	71	MCWhorter Recovery	1.03	0.06	2.1E-05	18.0
SJKF84#5	#8	5092.00	180	MCWhorter Recovery	0.07	0.004	1.4E-06	18.0
KF84-20(d)	#7	5213.92	190	MCWhorter Recovery	0.01	0.002	7.1E-07	5.0
Kf84-21C	#7	5219.66	75	MCWhorter Recovery	0.04	0.008	2.8E-06	5.0
Kf84-22B	#7	5204.10	140	MCWhorter Recovery	0.02	0.003	1.1E-06	5.0
Kf84-22C	#4-6	5142.50	202	MCWhorter Recovery	0.01	0.0014	4.9E-07	7.0
Kf84-20A	#2	5163.78	240	MCWhorter Recovery	0.009	0.001	3.5E-07	10.0
Kf84-22E	#2	5107.80	237	MCWhorter Recovery	0.01	0.001	3.5E-07	10.0

Most estimates of vertical hydraulic conductivities of confining units, such as the Fruitland Formation interburden, are obtained indirectly by model calibration. Kaiser et al (1994) performed regional hydrogeologic modeling of the Fruitland Formation and overlying and underlying formations. They found that large ratios of horizontal to vertical hydraulic conductivity (kh/kv) on the order of (1000/1) were required to simulate observed heads. The New Mexico Office of the State Engineer Aquifer Test Index provides an estimate of the vertical hydraulic conductivity of 1 x 10^{-5} ft/day for a confining zone in the Brushy Basin Shale member of the Morrison Formation based on a long-term pumping test at well 16u162 located in the San Juan Basin in T27N, R13W, Sec 16 about 13 miles east of the Navajo Mine.

Mine Spoils

Based upon laboratory determinations in Appendix 11-K of the Navajo Mine permit application package (BNCC, 2011), the hydraulic conductivity or permeability of the backfilled spoil will be on the order of 1.13 x 10^{-2} ft/day (4 x 10^{-6} cm/sec). Laboratory tests are thought to provide a lower bound estimate of hydraulic conductivity of mine spoils. Saturated spoils are not found in the Navajo Mine permit area that could be assessed with a well test. However, some of the mine spoil in the pre-law Bitsui Pit is saturated. Well tests have not been performed on these saturated spoils but future testing plans are being considered. In the mean time, the geometric mean of mine spoils of 2.268 x 10^{-1} ft/day (8 x 10^{-5} cm/sec) obtained from tests on mine spoils at a number of mines in the Northern Great Plains (Rehm et al, 1980) provides information on the expected hydraulic properties of mine spoil. Laboratory tests of mine spoils in Appendix 11-K also indicate that mine spoils will have a porosity of about 40%.