TALEN ENERGY

Appendix A

STAGE I & II EVAPORATION PONDS AREA GROUNDWATER CONCEPTUAL MODEL AND EXPANDED NUMERICAL MODEL

Colstrip Steam Electric Station
Colstrip, Montana

NewFields

june 2017

STAGE I & II EVAPORATION PONDS AREA GROUNDWATER CONCEPTUAL MODEL AND EXPANDED NUMERICAL MODEL

Colstrip Steam Electric Station
Colstrip, Montana

PPL Montana

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June 2017

EXECUTIVE SUMMARY

This report describes the expansion and calibration of a numerical groundwater flow model previously developed for the Stage I and Stage II Evaporation Ponds area of Colstrip Steam Electric Station (CSES) in Colstrip, Montana (**Figure ES-1**). The work described herein was completed by NewFields Companies LLC (NewFields) on behalf of Talen Energy (Talen), the current operator of the CSES.

On August 3, 2012, PPL Montana, LLC and the Montana Department of Environmental Quality (MDEQ) entered into an Administrative Order on Consent (AOC). As part of the AOC, Talen has committed to prepare Site Reports for the Plant Site, Stage I Evaporation Pond (SOEP), Stage II Evaporation Pond (STEP), and Units 3 & 4 Evaporation Holding Pond (3&4 EHP) areas. The AOC Site Reports are required to present information regarding groundwater models and results of modeling. This report presents methods and results of recent work to update and expand the previous conceptual and numerical groundwater model for the SOEP and STEP area, and is included as an appendix to the broader AOC site report for the SOEP and STEP area.

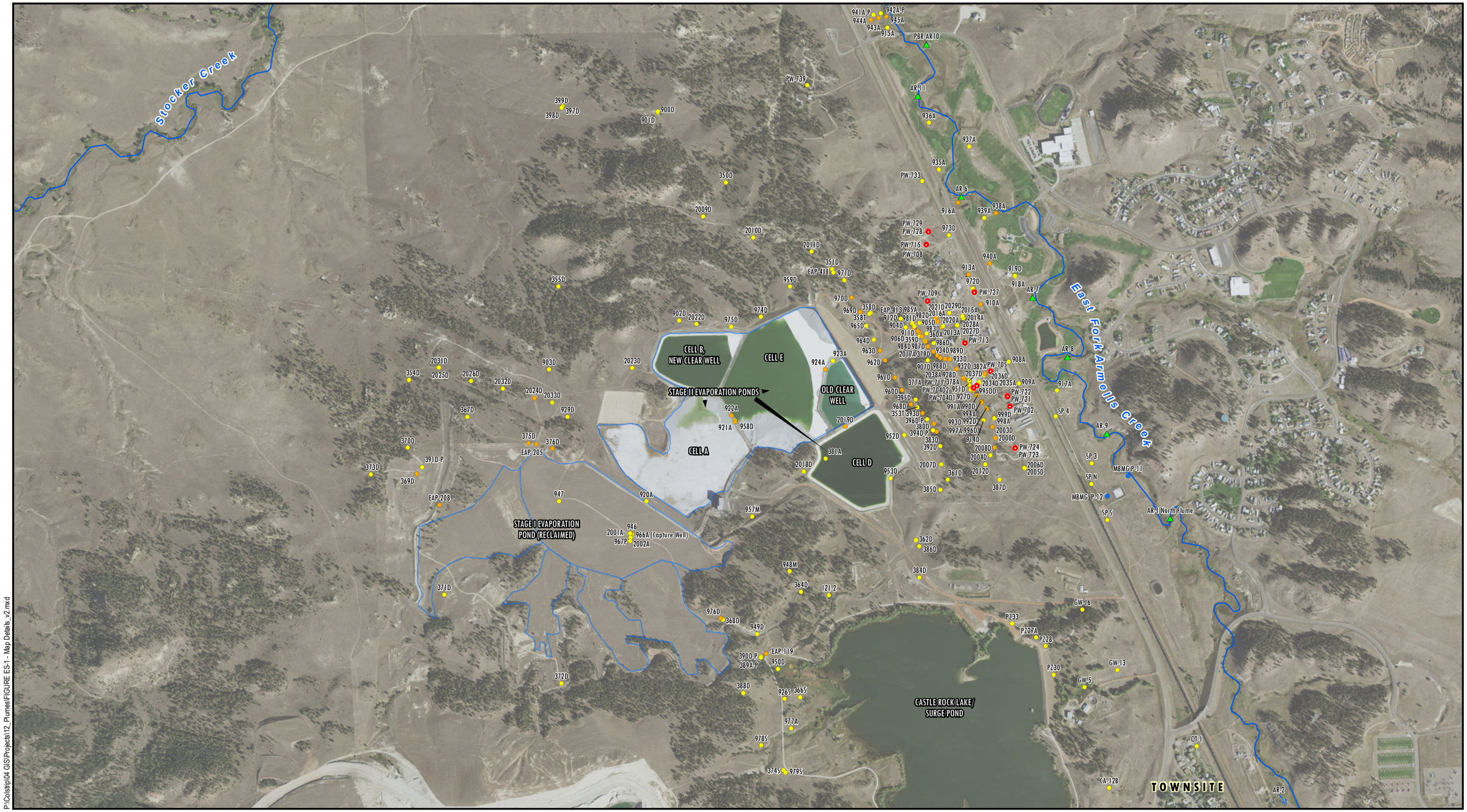
MODEL BACKGROUND

Maxim (2004) developed a preliminary conceptual model of the hydrogeologic system near the SOEP and STEP and Plant Site areas which included a characterization of process ponds and statistical analyses. A numerical groundwater flow model was developed for the STEP area using MODFLOW-2000 to provide a tool capable of simulating groundwater conditions downgradient of the STEP Main Dam (Maxim, 2005). Several options for hydraulic control were evaluated, including the potential use of a hydraulic barrier or groundwater capture wells. The numerical groundwater model domain of the SOEP and STEP area was expanded by NewFields (2014) and more detail in the model layering was added. The 2014 model has undergone an additional expansion (as described in this report) to include Stocker Creek and areas of the site upgradient of the Surge Pond.

GOALS AND OBJECTIVES

The overall goals of updating the numerical groundwater model are to:

1. Improve the basic understanding of the site groundwater system in the vicinity of the SOEP and STEP;
2. Provide a tool that will help to assess the current monitoring well network;
3. Help identify data gaps;
4. Evaluate the effectiveness of the site capture systems; and
5. Improve water management practices.



Note: 2015 NAIP Imagery

P:\Colstrip\04 GIS\Projects\12_Plumes\FIGURE ES-1 - Map Details_v2.mxd

0 Feet 1,200

NewFields

- Monitoring Well
- Capture Well
- Montana Bureau of Mines and Gelogy (MBMG) Well
- Deep Sub-McKay Private Wells
- Stream Gaging Station
- Pond

Site Map
SOEP and STEP Area
CSES-Colstrip, Montana
FIGURE ES-1

Specific objectives of completing the numerical groundwater update described in this report were to:

1. Adjust model layer geometry (as needed) to better reflect the actual hydrostratigraphy based on information obtained from wells recently installed;
2. Incorporate hydrogeologic information obtained since 2010 into the numerical model;
3. Expand the existing SOEP and STEP area groundwater model domain to move boundaries further away from pumping wells;
4. Calibrate the expanded model to a variety of head and flux data, including recently collected data; and
5. Use the calibrated model to assess the effectiveness of the groundwater capture system operating in the area near the SOEP and STEP.

GEOLOGY AND HYDROSTRATIGRAPHY

The Tongue River Member of the Fort Union Formation underlies the SOEP and STEP area. The formation dips 1 to 2 degrees to the southeast in the local area. The Tongue River Member consists of a 350–foot thick (maximum) sequence of interbedded siltstone, shale, and fine-grained silty sandstone as well as several coal seams. The principal coal seams in the area are the Rosebud and McKay at or near the land surface, and Robinson which is found at depth. The Tongue River Member is subdivided at the site into the following lithostratigraphic units; Rosebud Overburden, Rosebud Coal, Interburden, McKay Coal, and Sub-McKay. Overburden is not present in the SOEP and STEP area.

The depositional setting near the SOEP and STEP area created numerous lateral facies changes within the sedimentary rock deposits. Channel sandstones often grade laterally into siltstones or shale resulting in preferential pathways for groundwater flow. Clinker, which is overburden baked and altered by natural burning of underlying coal, is often present near where coal seams outcrop. Unconsolidated materials also overlie the Tongue River Member in several areas. These include colluvium located near the ridge tops and alluvium in drainage bottoms.

Groundwater flow is influenced by the presence of joints and fractures as well as stratigraphy. Stratigraphy has the greatest influence on preferential flow of groundwater. Groundwater preferentially moves through more permeable sand and gravel in alluvium and sandstone layers and lenses in bedrock relative to less permeable alluvial silt and siltstone, claystone, and shale. As sandstone lenses pinch out, groundwater flow can be diverted laterally.

Groundwater in the near-surface geologic units occurs in several strata. For purposes of the groundwater model, several hydrostratigraphic units were identified and incorporated into the model to increase the level of detail. These included:

- <u>Alluvium/Colluvium</u> – Alluvium, consisting of unconsolidated interbedded sand, gravel, clay and silt, occurs in four primary locations in the SOEP and STEP area. Clinker fragments are typically also found throughout finer-grained alluvial deposits. Alluvium is present primarily along the drainage bottoms, including tributary drainages, and near the STEP Main Dam. Colluvium present in the SOEP and STEP area are generally fine-grained unconsolidated sediments. These deposits occur at and near the land surface on hilltops, slopes and valleys.

- Rosebud Coal/Clinker – Clinker is a thermally altered rock also referred to as scoria. Clinker formed in areas where Rosebud Coal has burned, usually near where coal seams outcrop. This is most easily identified as red cap rock on hills around the region. Burning of the coal baked the overlying strata, reducing the coal volume, leaving a void for the overlying rock to collapse into or resulting in slow settling of the overlying rock into the space formerly held by the coal.
- Interburden – Interburden consists of siltstone, shale, and sandstone lying stratigraphically between the Rosebud and McKay Coal seams. This unit is missing from East Fork Armells Creek and Stocker Creek valleys due to erosion. It is also not present in many other areas of the site due to erosion with the exception of a few locations underlying Rosebud clinker deposits.
- McKay Coal – The McKay Coal seam is 0.2 to 15 feet thick in the model area and appears to be thickest south of the SOEP and STEP and sometimes contains carbonaceous shale. The McKay Coal is not present north and west of the SOEP, north and east of the STEP, and in the floodplain of the East Fork Armells Creek due to stream erosion.
- Sub-McKay Bedrock – The Sub-McKay bedrock unit includes interbedded and inter-fingered claystone, siltstone, fine-grained sandstone, and minor carbonaceous shale and coal stringers beneath the McKay Coal. The Sub-McKay unit is at least 300 feet thick and is present across the entire study area. This unit is divided into shallow and deep zones for the purposes of describing differences in groundwater flow, but the zones have similar lithostratigraphy. Sub-McKay bedrock is highly layered, which creates substantial anisotropy between horizontal and vertical hydraulic conductivity in the unit. Relatively high permeability sandstone layers and lenses are often interbedded with very low permeability siltstone/claystone layers with hydraulic conductivity values that can be six or seven orders of magnitude lower than sandstone layers. Some claystone units are so low in permeability that they will not yield water when drilled through and appear to be dry.

SURFACE WATER FEATURES

Several surface water features exist in the area near the SOEP and STEP. These include:

- East Fork Armells Creek;
- Castle Rock Lake (Surge Pond);
- SOEP (reclaimed but historically was an artificial fly ash pond surface water feature);
- STEP cells;
- Stocker Creek; and
- Golf course irrigation pond

The primary drainage in the area is the East Fork Armells Creek. East Fork Armells Creek exhibits gaining and losing reaches within the SOEP and STEP area. The stream serves as both a source and a sink to the near-surface groundwater systems. Castle Rock Lake, known as the Surge Pond, is an approximately 150-acre constructed impoundment that was built in 1974 to store water to be used for the coal-fired steam electric plant. Groundwater elevations are slightly above lake levels west of the lake and well below lake level north, east and south of the lake. The SOEP was operated between 1975 and 1997 and was constructed with a partial liner consisting of natural clay. During operation, fly ash scrubber slurry was pumped from the Plant Site into the pond through a fiberglass pipeline. Fly ash

settled in the pond and the water was periodically pumped back to the Plant Site for use as process water. The pond was determined to be full in 1997 and was reclaimed in 2002. The STEP consists of five cells that are lined with either high density polyethylene (HDPE) or reinforced polypropylene (RPP). Fly ash contained in scrubber slurry from Units 1 and 2 is pumped in a pipeline to the STEP Paste Plant which was constructed south of Cell A in 2009. The Paste Plant removes excess water from the scrubber slurry. This process increases the solids of the scrubber slurry from about 15 percent to about 65 percent. The paste is transported by pipeline to Cell E, where it hardens to a concrete-like material while binding, and immobilizing the residual water that helps reduce seepage. Seepage from these ponds is variable and locally affects groundwater elevations and flow directions in shallower units.

WATER QUALITY

Water quality in the SOEP and STEP area has been documented through an extensive surface water and groundwater monitoring program that has been active for decades and expanded over time. Dissolved constituents, including sulfate, magnesium, dissolved boron, and chloride, are present naturally in the regional groundwater system and are also potentially affected by land use upgradient from the SOEP and STEP area. These constituents are also present in process pond water at concentrations higher than background screening levels (BSLs).

Groundwater at and downgradient of the SOEP and STEP contains levels of indicator parameters (including total dissolved solids (TDS), specific conductance (SC), sulfate, chloride, and dissolved boron) that are elevated with respect to BSLs calculated by Neptune (2017). Current and former process ponds at the SOEP and STEP have likely served as sources of these parameters to groundwater. Most groundwater with concentrations of constituents above BSLs is currently being intercepted by the groundwater capture wells and toe drain below the STEP Main Dam and returned to lined ponds. Groundwater containing concentrations of a single indicator parameter exceeding BSL's is not a clear indication that groundwater has been impacted by process waters. Chloride, for example, is considered a secondary indicator parameter in this report because the chloride BSLs appear unrepresentative of site background conditions. In order to assess whether groundwater at a well has been affected by process water, the constituent concentrations, water quality trends, groundwater flow, and location must all be taken into account.

CONCEPTUAL MODEL

Figure ES-2 is an animated block model (paper copies of this report contain a static image) illustrating our conceptual understanding of the hydrogeologic system in the SOEP and STEP area. Groundwater flow in shallow bedrock and alluvium generally flows northeast under the SOEP and STEP and then turns northwest parallel to East Fork Armells Creek. Groundwater flow in the deep Sub-McKay follows a more regional pattern that is generally from southwest to northeast beneath the SOEP and STEP area. Vertical hydraulic gradients in all well pairs evaluated are downward from alluvium to the Shallow Sub-McKay and into capture wells or the underlying deep Sub-McKay.

Underflow is the major source of water entering the groundwater system in the SOEP and STEP area making up about 65 percent of the inflow. Areal recharge (background and clinker) and infiltration through the SOEP account for 15 percent and 3 percent, respectively, of water entering the groundwater system. Seepage from the surge pond provides an estimated 14 percent of the groundwater inflow. Although the process ponds are lined, some seepage might occur that reaches the

groundwater system, creating localized mounding. Seepage from single-lined STEP cells (A, E, and Old Clearwell) accounts for the remaining 3 percent of inflow to the groundwater system.

Underflow out is about 62 percent of system outflow. Groundwater capture via drains and wells is another major source of outflow for the groundwater budget, estimated to be about 28 percent of water leaving the groundwater system. Some shallow groundwater enters gaining reaches of East Fork Armells Creek and Stocker Creek and accounts for 8 percent and 2 percent, respectively, of water leaving the groundwater system.

Most groundwater with concentrations of constituents above BSLs is currently being intercepted by the groundwater capture system and returned to lined ponds. Some of this groundwater is also being captured by the toe drain at the base of the STEP Main Dam. The capture system depresses the water table and collects both impacted and non-impacted groundwater. The current capture system is preventing east-flowing groundwater from the SOEP and STEP area from entering East Fork Armells Creek alluvium. Groundwater that is not captured by pumping in the vicinity of the SOEP generally flows very slowly to the northeast.

Process pond water contains dissolved constituents that are also present in upgradient groundwater that is un-impacted by sources within the SOEP and STEP area, making it difficult to draw distinct lines between impacted and un-impacted groundwater. Groundwater quality that is influenced by current and former process ponds at the SOEP and STEP area is characterized by levels of parameters such as dissolved boron, chloride, SC, sulfate, and TDS that are elevated as compared to groundwater in areas not affected by process ponds.

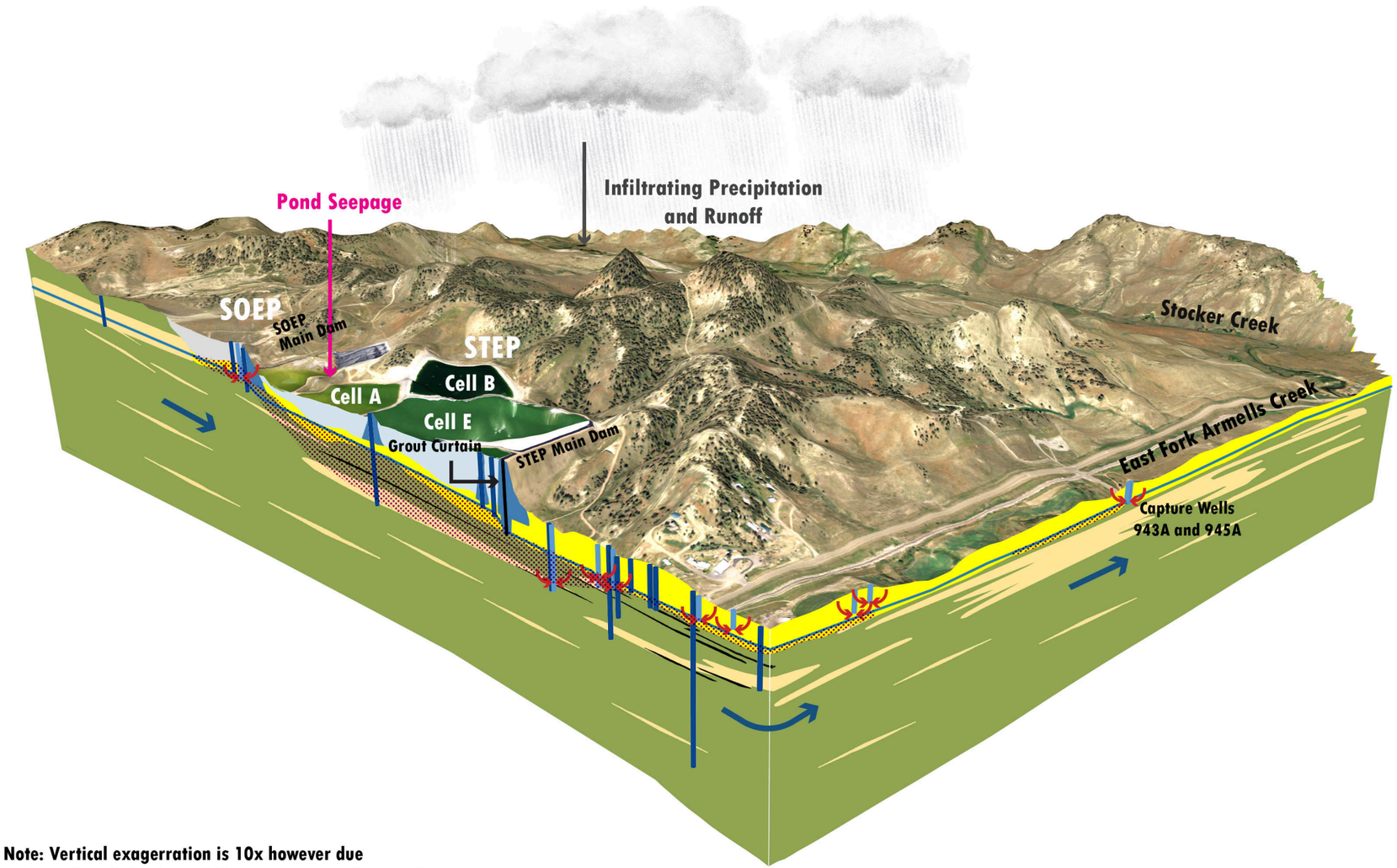
Currently, groundwater is not used for domestic or livestock purposes in the SOEP and STEP area. One exception is well 901D that in 2015 was equipped with a pump for seasonal stock water use.

MODEL DESIGN

The current SOEP and STEP model includes refinements to the previous model developed by NewFields (2014). The primary refinements include adjustments to model boundaries, layer elevations, grid discretization, and assignment of model properties based on data collected through October 2014. The model geometry and discretization were refined to more accurately simulate groundwater flow in distinct stratigraphic intervals. The conceptual model provides the foundation for the refinements made in the development and parameterization of the current SOEP and STEP model.

In revising the model, NewFields expanded the domain to move external model boundaries farther from the area of interest and pumping of capture wells. Expansion of the domain was also prompted by review of potentiometric surfaces for the deepest portion of the model. Review of expanded potentiometric surface maps for the deep Sub-McKay system suggested that deeper regional flow is northeasterly and crosses under East Fork Armells Creek.

Layer bottom elevations were assigned based on contacts of lithostratigraphic units and were further divided to provide greater resolution for heads and flow, and to better match the screened intervals of monitoring and capture wells. Model layer elevations were adjusted in several portions of the model based on lithologic contacts from well logs for new wells installed since 2010. Adjustments were made such that layer transitions correspond with lithologic contacts.



Note: Vertical exagerration is 10x however due
to skewed angle horizontal distances appear shortened

Note: See Figure 2-1 for location of block model.

- Capture Well
- General GW Flow
- Fly Ash
- Alluvium
- Fill Material
- Constituent Concentrations Exceeding BSLs
- Monitoring Well
- Potentiometric Surface
- Coal
- Siltstone/Claystone
- Sandstone

0 Feet 1,000

NewFields

SOEP and STEP Area Conceptual Block Model
SOEP and STEP Area
CSES-Colstrip, Montana
FIGURE ES-2

The primary changes incorporated in the current SOEP and STEP model include the following:

- Domain: The model domain was expanded to the north of Stocker Creek and to the east side of East Fork Armells Creek;
- Layer Elevations: Model layer elevations were adjusted in several portions of the model based on lithologic contacts from well logs for new wells installed since 2010 and to better represent hydrostratigraphy and hydraulic communication, and within a sandstone layer hosting capture well 958D;
- Recharge: Additional recharge zones were added to represent the Evaporation Pad (located at the just north of Cell A), Cell D, and Clinker outcrops;
- General Head Boundaries: GHB Package cells were added to Layer 5 and 6 to represent underflow flowing into and out of the model domain;
- Pumping Rates: Pumping rates were adjusted to reflect new estimates of pumping rates;
- Pumping Wells: Additional pumping wells were added to the model to reflect expansion of the capture system between 2010 and October 2014;
- Calibration Data: The model was calibrated to new data sets (including new pumping test results), and datasets were revised to represent October 2005 and 2014 steady-state conditions; and
- East Fork Armells Creek Alluvium: Alluvium along the creek was changed to be simulated as fine-grained sediments overlying coarse-grained sand and gravel.

MODEL CALIBRATION

Following revision of the model framework and boundaries and assignment of initial model parameters, the current SOEP and STEP Model was calibrated to provide a measure of confidence in its ability to meet project objectives. The calibration process required establishing a set of calibration targets and then performing an iterative process comparing model results with the targets. Targets used to calibrate the current model included: (1) measured water levels, (2) estimated flux into and out of the groundwater system as underflow, (3) net gains and losses in East Fork Armells Creek, (4) closeness of fit between simulated and observed potentiometric maps, and (5) closeness of fit between simulated and observed hydrographs and time-drawdown plots from aquifer tests.

During calibration, input parameters values were varied iteratively within the range of values determined through field measurements and literature values. Input parameters varied during calibration included:

- Hydraulic Conductivity (varied within ranges described for each lithostratigraphic unit);
- Pond Seepage (varied within ranges estimated in the water balance discussion);
- Background Recharge (varied within estimated range provided in the water balance discussion);
- Conductance of Head-Dependent Boundaries (varied with changes for the assigned hydraulic conductivity of the adjacent cell);
- Storage adjusted in transient calibration (varied within ranges reported from aquifer tests and literature values for similar lithologies); and
- Surface water elevation in the East Fork Armells Creek.

The model was calibrated to several independent hydrologic data sets to evaluate how robust the model was under both steady-state and transient simulations. These include comparing model output to measured heads and estimated fluxes for two time periods (2005 and 2014) for steady-state conditions, to measured drawdown associated with two pumping tests, and to transient head and flux data collected between November 2005 through December 2007.

The major parameter adjusted during model calibration was hydraulic conductivity. Pond seepage rates were also adjusted within reasonable ranges. During transient calibration, recharge rates and storage parameters were adjusted most frequently with fewer adjustments to hydraulic conductivities other than adjustments made as a result of steady-state calibration. Particle-tracking was periodically performed to check the match between simulated and observed movement of process pond-affected groundwater. Calibration results were evaluated against modeling calibration goals.

Results indicate that the current SOEP and STEP Model is well-calibrated. Calibration to several independent sets of steady-state and transient data provides confidence in the ability of the model to simulate flow and advective transport under a variety of hydrogeologic conditions within a reasonable range of error.

SENSITIVITY ANALYSES

A sensitivity analysis was performed to quantify uncertainty in the calibrated model relative to uncertainty in model inputs. The sensitivity analysis was conducted using the 2014 steady-state simulation by varying selected model input values within plausible ranges to document the effect on model calibration statistics. Parameters that appeared to have the greatest effect on residual statistics during manual and automated calibration were selected for analysis, including:

- Horizontal and vertical hydraulic conductivity;
- Net recharge rates (background and clinker);
- Pond seepage rates;
- Conductance of River Package cells simulating East Fork Armells Creek; and
- Capture well pumping rates.

Results of the sensitivity analysis show that the model calibration is most sensitive to the following:

- Increases and decreases in horizontal hydraulic conductivity for Zone 12 - Shallow, Mid-, and Deep Sub-McKay Interbedded Siltstone and Sandstone in Layers 2, 3, 4 and 5;
- Decreases in horizontal hydraulic conductivity for Zone 49 – Alluvium in Layers 2, 3, and 4;
- Increases in Background and Clinker area recharge; and
- Increases in pond seepage at SOEP and Cell A.

Overall, the sensitivity analysis shows the current SOEP and STEP Model is relatively well-calibrated with increasing recharge (pond seepage) having the greatest effect on the model calibration, while both increasing and decreasing distinct hydraulic conductivity zones also have measurable effects on model calibration. Model calibration appeared to be relatively insensitive to increases and decreases in river bed conductance. The sensitivity analysis also shows that the parameter specifications for the calibrated model are appropriate for evaluating site conditions and for particle tracking.

PARTICLE TRACKING AND CAPTURE ANALYSIS

Particle tracking was used to evaluate the effectiveness of the current groundwater capture system. For this analysis, particles were placed in portions of Layers 2 through 6 in the model in areas that currently exceed BSLs for indicator parameters. Separate simulations were run for particles beneath the source areas (i.e. SOEP, STEP A Cell, and STEP E Cell) and areas above BSLs but outside the source areas. Particles were allowed to move forward in time and results were evaluated to determine if any portion of the groundwater system that currently exceeds BSLs is not being captured by the current groundwater capture system.

Particle tracking suggests that groundwater exceeding BSLs for indicator parameters originating from most known source areas in the SOEP and STEP area will be intercepted by the capture system and that groundwater in most of the areas exceeding the BSLs are contained. Capture analysis results also suggest that the current capture system may not be completely capturing groundwater originating from some areas within 50 years, including:

- Groundwater beneath the north and northwestern edges of the SOEP;
- Groundwater beneath the southwest and south edges of the SOEP;
- Groundwater beneath the northern edge of the Cell A and Cell E;
- Groundwater beneath Cell A along the western edge and under the Evaporation Pad;
- Groundwater in areas of BSL exceedance beneath Cell B;
- Areas of BSL exceedance north and northwest of the SOEP;
- Areas of BSL exceedance southeast of the SOEP;
- Areas of BSL exceedance northwest of Cell A and the Evaporation Pad and southeast of Cell A ; and
- Areas of BSL exceedance in East Fork Armells Creek alluvium northwest of well 938A and 939A and a few smaller areas to the southeast of those wells that flow toward the creek. Much of this area exceeds BSLs for chloride only and therefore is interpreted not to be related to the closed loop wastewater system.

CONCLUSIONS AND RECOMMENDATIONS

Calibration of the numerical groundwater flow model described in this report demonstrates the model is capable of simulating groundwater flow and advective transport under a variety of hydrogeologic conditions. The numerical model is appropriate for use in evaluating elements of the conceptual model and the efficacy of groundwater capture systems, either currently operating or being considered in the future.

Development of the conceptual and numerical groundwater flow model, along with model calibration, model sensitivity analysis, and capture analysis, have led to the following conclusions:

- The STEP and SOEP area has a complex and dynamic groundwater flow system. In addition to complex hydrostratigraphy and diverging groundwater flow, seepage from cells in the STEP and Surge Pond influence groundwater flow in the area.

- Groundwater quality that has been influenced by SOEP and STEP is characterized by elevated levels of several parameters, including dissolved boron, chloride, sulfate, magnesium and SC.
- Vertical hydraulic gradients for measured paired wells are generally downward across the site.
- Much of the seepage from the SOEP and STEP infiltrates into underlying alluvium and bedrock and flows northeast toward East Fork Armells Creek. In 2004, groundwater exceeding BSLs flowed into East Fork Armells Creek alluvium and then northwest parallel to the creek. In the last several years, the groundwater capture system has cut off the plume in groundwater beneath the drainage east of the STEP Main Dam before it enters East Fork Armells Creek alluvium. Some groundwater exceeding BSLs has migrated a small way north of the STEP although migration in this area appears to be very slow. A small area of uncaptured bedrock and alluvial groundwater exceeding BSLs is located south of the SOEP and west of the Surge Pond.
- BSLs recently recalculated for area groundwater are in some cases substantially lower than previously estimated BSLs. In particular, the chloride BSL for alluvium dropped from 213 mg/L to 45 mg/L, which has greatly expanded the area of East Fork Armells Creek alluvium exceeding the BSL for chloride. Some chloride detected in East Fork Armells Creek alluvium could originate from sources other than the SOEP and STEP, and the ponds may not be the source of chloride detected in that area. For this reason chloride is considered to be a secondary indicator parameter.
- Between 2005 and 2014, installation of several alluvial and bedrock capture wells and rehabilitation of well 360A between the STEP Main Dam and East Fork Armells Creek improved groundwater capture system effectiveness thereby reducing concentration of indicator parameters in alluvium and bedrock well in this area.
- Concentrations of indicator parameters in alluvial monitoring wells east of Cell D (377A, 382A, 994A, 997A and 998A) exhibit decreasing trends indicating that groundwater capture wells installed in this area since 2008 are effectively capturing groundwater prior to its reaching East Fork Armells Creek alluvium.
- The numerical groundwater flow model has been calibrated to multiple sets of hydrogeologic data that represent a range of conditions and is able to reproduce flow fields, heads, and fluxes within a reasonable range of error under a variety of hydrologic stresses. This robust calibration procedure provides confidence in the predictive capabilities of the model.
- The model calibration is most sensitive to increases in horizontal hydraulic conductivity and pond seepage rates.
- Capture analysis indicates the groundwater capture system is currently capturing all groundwater originating from the SOEP and STEP that flows east before it reaches alluvium associated with East Fork Armells Creek. Groundwater exceeding BSLs in alluvial monitoring wells adjacent to East Fork Armells Creek is likely either residual from before the implementation of the latest capture system or is from sources other than the SOEP and STEP.
- Capture analysis indicates particles within an area where groundwater exceeds BSLs for several indicator parameters in the northwest portion of the SOEP area are partially captured by wells 2024D, EAP-205, 375D, and 376D. According to the model, some uncaptured particles in this area travel north toward monitoring wells 354D, 2025D, 2026D, and 2031D. However, groundwater samples from these wells do not currently exceed BSLs for indicator parameters.

- Particles representing groundwater originating in the northwest half of the SOEP area are partially captured by wells 2024D, EAP-205, 375D, and 376D. Particles released north of this area near wells 903D, 2032D, 2033D and 929D are not captured (although many particles released south of this area are captured by well 2024D). The model indicates that particles that are not captured in this area would move north toward well 355D, which has not exhibited evidence of process pond impacts.
- Capture analysis indicates particles within an area where groundwater exceeds BSLs for several indicator parameters immediately north of STEP Cell A and Cell B near wells 2022D and 2023D are not captured. The model indicates that particles originating near 2022D travel north toward wells 398D, 399D, and 901D, and particles originating near 2023D travel north toward 2009D. Groundwater samples from wells 398D, 399D, 901D have not exceeded BSLs, and samples from well 2009D slightly exceed the BSL for sulfate but not BSLs for dissolved boron, chloride, or SC. However, there are no indications of impacts from process water at this location, as sulfate levels have shown a slight decline while all other indicators are stable.
- Groundwater that exceeds BSLs in areas north of the SOEP and STEP appears to be moving very slowly due to relatively low permeability (with the exception of near well 2024D). This results in low yield wells and is a major reason for lack of complete capture in this area.
- The capture system below the STEP dam effectively cuts off contaminated source water from traveling east to East Fork Armells Creek Alluvium.
- Results of reverse particle tracking analyses suggest groundwater at wells 366S, 374S, 926S, 977A, 978S, and 979S containing concentrations of indicator parameters exceeding BSLs originates from upland areas south of those wells and not from the SOEP area.
- Uncertainty analysis indicates that predicted groundwater capture analysis is not very sensitive to decreases in capture well pumping rates on the order of 25 percent.

In developing the conceptual and numerical models potential data gaps were identified. NewFields recommends the following work to fill data gaps:

- Even though simulation of plume capture using particle tracking was not sensitive to overall decreases of current capture rates, future capture analyses that might consider fewer active pumping wells and/or lower pumping rates might be sensitive to this parameter. Developing a more accurate method of measuring capture well pumping rates would increase model accuracy.
- The downgradient extent of areas exceeding BSLs between wells 2022D and 2009D is uncertain. Monitoring well(s) should be installed in bedrock between wells 2022D and 2009D to evaluate the downgradient extent of process pond-affected groundwater and the feasibility of additional capture in this area based on well yield.
- Monitoring well(s) should be installed in bedrock north of well 2032D to evaluate the downgradient extent of process pond-affected groundwater and the feasibility of additional capture in this area based on well yield. Screening wells or extending sand-pack around the screen over a larger saturated interval than 2032D would accommodate potential capture.
- It appears more capture is needed near well 903D based on concentrations of parameters exceeding the updated BSLs. It is recommended the feasibility of converting 903D to a capture well be evaluated. If this is not feasible, installation of an additional well in this area should be considered to evaluate feasibility of additional capture based on well yield.

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1.0 INTRODUCTION

This report describes the expansion and calibration of a numerical groundwater flow model previously developed for the Stage I and Stage II Evaporation Ponds area of Colstrip Steam Electric Station (CSES) in Colstrip, Montana (**Figure 1-1**). The work described herein was completed by NewFields Companies LLC (NewFields) on behalf of Talen Energy (Talen), the current operator of the CSES. PPL Montana, LLC initiated groundwater modeling efforts in this area in 2004 to develop a better understanding of the hydraulic interactions between process ponds, groundwater capture systems, and surface water at and near the facility in an effort to mitigate existing (see below) and potential future pond seepage impacts to the environment.

On August 3, 2012, PPL Montana, LLC and the Montana Department of Environmental Quality (MDEQ) entered into an Administrative Order on Consent (AOC) entitled "*Administrative Order on Consent Regarding Impacts Related to Wastewater Facilities Comprising the Closed-Loop System at the Colstrip Steam Electric Station*" (MDEQ/Talen Montana, 2012). As part of the AOC, Talen has committed to prepare Site Reports for the Plant Site, Stage I Evaporation Pond (SOEP), Stage II Evaporation Pond (STEP), and Units 3 & 4 Evaporation Holding Pond (3&4 EHP) areas (**Figure 1-1**). The AOC Site Reports are required to present information regarding groundwater models and results of modeling. This report presents methods and results of recent work to update and expand the previous conceptual and numerical groundwater model for the SOEP and STEP areas, and is included as an appendix to the broader AOC site report for the SOEP and STEP areas.

The current model is being used to help evaluate remedial alternatives. As such, updating the model within the two year time frame will pose problems and delay the current AOC process. It is appropriate for the next model update to occur after remedy selection but before remedial design. Following approval of the remedial alternative evaluation, the conceptual and numerical models will be updated every two years, or when sufficient new information has been collected to warrant model updates. During the update process all new hydrogeologic information collected since this last model update will be incorporated into the conceptual model. This information will include additional lithologic, stratigraphic, and aquifer testing data from any new wells installed since the last model update. It will also include recent climatic, streamflow, groundwater elevation, and water quality data.

1.1 SITE DESCRIPTION

The CSES is a four-unit coal-fired electrical generation facility located near the Town of Colstrip (**Figure 1-1**). Colstrip Units (Units) 1 and 2 are 333-megawatt, coal-fired steam electric generating units that have been in use since 1975. Units 3 & 4 are 800-megawatt generating units that began producing power in October 1983 and April 1986, respectively.

The Yellowstone River is the source of water used for Units 1 through 4. Water is piped from the river to Castle Rock Lake (Surge Pond), west of the Colstrip Townsite, and then to the various Units. Water is used for various purposes, including cooling of the Units, within the scrubbers, and for creating slurries to transport fly ash and bottom ash to nearby settling and evaporation ponds.

There are three general areas of process ponds associated with the CSES (**Figure 1-1**): the Plant Site, Units 3 and 4 EHP, and the SOEP and STEP areas. The SOEP and STEP areas, the focus of this report, are about two miles northwest of the Plant Site and include the SOEP and STEP that accept scrubber slurry from Units 1 and 2. A map of the SOEP and STEP Area is shown on **Figure 1-2**. The Block Model outline on **Figure 1-2** is discussed in **Section 2.8**. The Plant Site includes several process ponds near Units 1 through 4. The Units 3 and 4 EHP are located approximately 2.5 miles southeast of the Plant Site. Process pond seepage, pipeline spills and incidental tears in pond liners have resulted in impacts to groundwater and surface water quality in various portions of the facility.

1.2 MODELING BACKGROUND

Maxim (2004) developed a preliminary conceptual model of the hydrogeologic system near the SOEP and STEP and Plant Site areas (**Figure 1-2**). Maxim (2004) included a characterization of process ponds and statistical analysis of baseline groundwater quality in their report. The document describes hydrostratigraphy, aquifer characteristics, groundwater flow, and interactions between surface water and groundwater. The report also discusses contaminant transport pathways and potential receptors.

A numerical groundwater flow and transport model was developed for the STEP area to provide a tool capable of simulating groundwater flow and solute transport downgradient of the STEP Main Dam. The model was developed to evaluate hydraulic control techniques to prevent off-site migration of groundwater affected by leakage from the ponds. Maxim (2005) summarized the conceptual model of groundwater flow and advective transport in the STEP, described the initial numerical model design, and discussed model calibration methods and results. The initial STEP area model was developed using the U.S. Geological Survey (USGS) code MODFLOW-2000 (Harbaugh et al., 2000), and is summarized in **Table 1-1**. Several options for hydraulic control were evaluated, including the potential use of a hydraulic barrier or groundwater capture wells to abate the migration of process pond-impacted groundwater from Talen property.

Table 1-1. Comparison of Previous and Current Numerical Groundwater Model Features

Model	No. of Model Layers	Layer 1 Represents:	Deeper Layer(s) Represent:	Domain Size	Calibration Data Sets	Bottom Elevation of Model (feet amsl)
Maxim (2005) Model	3	Alluvium and Shallow Bedrock	Layer 2: Bedrock above elevation 3,100 feet amsl Layer 3: Bedrock beneath Layer 2 down to elevation 2,875 feet amsl	9,000 feet by 5,400 feet	2003 Steady-State (pre-pumping) 2004 Steady-State (post-pumping)	2,875
NewFields (2014) Model	8	STEP liners, surge ponds	Layer 2: Fly Ash (SOEP), upper Alluvium, upper Colluvium, Layer 3: lower Interburden, McKay Coal, middle alluvium Layer 4: upper sub-McKay, basal alluvium Layer 5-8: middle Sub-McKay through sub-Robinson	11,800 feet by 14,000 feet	2003 Steady-State 2004 Steady-State 2007 Steady-State 2005-2007 Transient 2009 Steady-State 2010 Steady-State 958D Pumping Test	2,864
Current Model	8	STEP liners, surge ponds	Layer 2: Fly Ash (Stage I), upper Alluvium, upper Colluvium, Layer 3: lower Interburden, McKay Coal, middle alluvium Layer 4: upper sub-McKay, basal alluvium Layer 5-8: middle Sub-McKay through sub-Robinson	16,500 feet by 14,000 feet	October 2005 Steady-state 2005-2007 Transient October 2014 Steady-state Several Pumping Tests (see report text)	2,875

Note: amsl – above mean sea level

Geomatrix (2007) updated the conceptual model of the SOEP and STEP areas. The updated conceptual model included refined interpretations of aquifer characteristics, groundwater flow, and groundwater chemistry based on the installation and testing of new groundwater monitoring and capture wells and the continued routine monitoring of water levels and chemistry in existing wells.

The numerical groundwater model domain of the SOEP and STEP areas was expanded by NewFields (2014) and more detail in the model layering was added (see **Table 1-1**). The 2014 model has undergone an additional expansion (as described in this report) to include Stocker Creek and areas of the site upgradient of the Surge Pond (**Figure 1-2**). A summary of the updated (current) numerical groundwater model is presented in **Table 1-1**. The current model details are further explained in **Section 3.0**.

1.3 GOALS AND OBJECTIVES

The overall goals of updating the numerical groundwater model are to:

6. Improve the basic understanding of the site groundwater system in the vicinity of the SOEP and STEP;
7. Provide a tool that will help to assess the current monitoring well network;
8. Help identify data gaps;
9. Evaluate the effectiveness of the site capture systems; and
10. Improve water management practices.

Specific objectives of completing the numerical groundwater model update described in this report were to:

1. Adjust model layer geometry (as needed) to better reflect the actual hydrostratigraphy based on information obtained from wells recently installed;
2. Incorporate hydrogeologic information obtained since 2010 into the numerical model;
3. Expand the existing SOEP and STEP area groundwater model domain to move boundaries further away from pumping wells;
4. Calibrate the expanded model to a variety of head and flux data, including recently collected data; and
5. Use the calibrated model to assess the effectiveness of the groundwater capture system operating in the area near the SOEP and STEP.

2.0 CONCEPTUAL MODEL

This chapter summarizes the hydrogeologic conceptual model for the SOEP and STEP areas, including updates to the original conceptual model (Maxim, 2004) and subsequent refinements (Geomatrix, 2007 and NewFields, 2014). The current conceptual model, described below, is inclusive of all previous conceptual models, updated and revised as appropriate with new data. The following new information was incorporated into the conceptual and numerical models discussed in this report:

- Lithologic information, water level data, and water quality data for wells 2019D through 2038A **Figure 2-1**); these wells were installed south of the SOEP, in alluvium beneath the SOEP, and in areas north, east, and south of the STEP Main Dam;
- Water level data obtained from all wells obtained between 2010 and October 2015;
- Water quality data obtained between 2010 and November 2015;
- Aquifer test data (20 pumping and slug tests) obtained between 2010 and 2015 at wells 2003D through 2038A;
- Synoptic gaging data collected on East Fork Armells Creek between 2010 and March 2015; and
- Regional groundwater level data from the Montana Bureau of Mines (MBMG) Groundwater Information Center (GWIC, 2016) for establishing elevations at model edge boundaries.

Included in this chapter are descriptions of geology, hydrostratigraphy, aquifer characteristics, groundwater flow, interactions between surface water and groundwater, water quality, and water balance. A summary of the conceptual model is included at the end of this section.

Note that the elevation datum used for this study is in North American Vertical Datum (NAVD) 1988 unless otherwise noted. The only data that uses the older National Geodetic Vertical Datum (NGVD 1929) is the surface elevation data obtained from the USGS, which requires an upward adjustment of 2.303 feet to bring it into the newer datum. Similarly, the spatial location datum used is the North American Datum (NAD) 1983, which replaced the older NAD 1927 datum.

2.1 LITHOLOGIC AND HYDROSTRATIGRAPHIC UNITS

The following subsections provide descriptions of our current understanding of the regional and site geology and hydrostratigraphy of the SOEP and STEP areas, as updated using recently collected data and information.

2.1.1 Regional Geology

The SOEP and STEP area is located in the northern portion of the Powder River Basin, an asymmetrical basin oriented northwest to southeast. The orientation of this structural basin is largely responsible for the general regional orientation of the bedding associated with the various geologic units in the area. The near-surface geology in the area is dominated by the Fort Union Formation which includes strata that generally dip gently (less than a few degrees) to the east in the western portion of the site and to the south in the eastern portion, across the coal field. In some localized areas of the CSES vicinity, high-angle faults are present that steepen dips (Roberts et al., 1999).

Stratigraphy in the SOEP and STEP area and more regionally consists of, in descending order, the Fort Union Formation, Hell Creek/Lance Formation, Fox Hills Sandstone, and Bearpaw Shale. The Fort Union Formation is divided into three members; the upper Tongue River Member, the middle Lebo Shale Member, and the lower Tullock Member. The Tongue River Member is exposed at the surface in the general vicinity of the SOEP and STEP. The Lebo Shale and Tullock Member are exposed north of the Site. At Colstrip, the total thickness of the Fort Union Formation is about 650 feet.

The Fort Union Formation consists of alternating and intercalated deposits of shale, claystone, mudstone, siltstone, sandstone, carbonaceous shale, and coal. The formation was deposited in a fluvial system of meandering, braided, and anastomosed streams near the basin center and by alluvial fans at the margins. The fluvial systems associated with the Fort Union Formation were typically oriented northeast-southwest (Flores and Ethridge, 1985).

Numerous coal seams are present within the Tongue River Member of the Fort Union Formation. A tropical to sub-tropical climate created an environment in which thick peat deposits accumulated in swamps and bogs (Nicols et al., 1989; Flores et al., 1999) which ultimately led to the formation of the coal seams. Because of the depositional setting in which bogs or channels terminate or have bounds, the coal beds may pinch out laterally or stop abruptly. The main coal seams of interest near the CSES are the sub-bituminous Rosebud (about 24 feet thick) and McKay seams (about 8-10 feet thick) which can economically be strip-mined. These two coal seams merge into a single seam on the west side of the Little Wolf Mountains near the Absaloka Mine. The Rosebud Coal, however, is the only seam mined in the area due to inferior quality of the McKay Seam which makes it undesirable for use in many coal-fired boilers. Both the Rosebud and McKay Coals are generally cleated, containing natural vertical fractures generally oriented perpendicular to the bedding plane.

Cementation (the chemical binding of individual grains to one another) is highly variable within the units and mostly occurs as weak calcium carbonate cement although thin deposits with silica cementation also are present. Localized thin limestone beds also are infrequently present in the geologic package in the region.

2.1.2 Site Geology and Lithologic Units

The Tongue River Member of the Fort Union Formation underlies the SOEP and STEP areas. The formation dips 1 to 2 degrees to the southeast in the local area. The Tongue River Member consists of a 350-foot thick (maximum) sequence of interbedded siltstone and fine-grained silty sandstone as well as several coal seams. The principal coal seams in the area are the Rosebud, McKay, and Robinson coal units. The Rosebud and McKay may be at or near the land surface while the Robinson is found at depth. The Tongue River Member is subdivided into the following lithostratigraphic units at the site: Rosebud Overburden, Rosebud Coal, Interburden, McKay Coal, and Sub-McKay. Rosebud Overburden is not present in the SOEP and STEP areas.

The depositional setting near the SOEP and STEP areas created numerous lateral facies changes within the sedimentary rock deposits. Channel sandstones often grade laterally into siltstones or shale resulting in preferential pathways for groundwater flow. Clinker, which consists of burned coal and baked and altered overburden, also is present near where coal seams outcrop, as a result of natural burning of coal. Unconsolidated materials also overlie the Tongue River Member in several areas. These unconsolidated materials include colluvium located near the ridge tops and alluvium in drainage

bottoms. Each general lithostratigraphic unit is described below in terms of texture and extent in the SOEP and STEP areas. Lithology and hydrostratigraphy were examined in detail in support of the model refinement described in this document. Lithologic logs from wells located in the SOEP and STEP area (**Figure 2-1**) were reviewed to delineate the areal extent and elevation of contacts between alluvium and bedrock and between major coal, sandstone, and siltstone strata. In addition to using well logs, the lateral extent of the various lithologic units (**Figure 2-2**) was determined using aerial photos, geologic maps, mine extent maps and 1971-era USGS topographic maps.

Vuke et al. (2001) shows a southwest – northeast trending fault that extends to just west of the STEP. This fault may extend beneath the historic drainage beneath the SOEP and STEP. There is no evidence that this fault is either a conduit for, or barrier to, groundwater flow.

Harding-Lawson (1975) identified jointing patterns near both ends of the Surge Pond dam trending at N35°W, and others were observed parallel to the Surge Pond dam outlet structure trending at approximately N85°E. Harding-Lawson (1975) also attributed seepage from the downstream side of the right dam abutment to suspected pathways in the joints. Bechtel (1982) reported near vertical joints trending N80°W and N20°E near the Surge Pond. Bechtel (1976) interpreted loss of circulation water during drilling in several drill holes surrounding the SOEP area to be indicative of fractures. Some fracture zones in bedrock may form preferential pathways for groundwater flow and constituent transport (Maxim 2004). Preferential groundwater flow is described further in **Section 2.4.2**.

2.1.2.1 Alluvium/Colluvium

Unconsolidated surficial sediments, consisting of alluvium and colluvium, are present at the SOEP and STEP area at the locations shown on **Figure 2-2**. Alluvium, consisting of interbedded sand, gravel, clay and silt, occurs in four primary locations in the SOEP and STEP area. Clinker fragments are typically also found throughout finer-grained alluvial deposits. Alluvium is present primarily along the drainage bottoms. These alluvium locations include:

- East Fork Armells Creek. This is the most prominent alluvial deposit and is comprised largely of Recent-aged relatively coarse grained deposits. The ancestral East Fork Armells Creek eroded through the shallow bedrock, Rosebud and McKay Coals, and in some places into the sub-McKay deposits. At the eastern edge of the SOEP and STEP, alluvial deposits of clay, silt, sand, and gravel reach thicknesses of 35 feet or more. The basal gravel associated with the alluvium typically follows East Fork Armells Creek;
- Stocker Creek. Alluvium is present along the channel of Stocker Creek, an ephemeral drainage lying northwest of the STEP that is a tributary to the East Fork Armells Creek. These deposits are less extensive than those of East Fork Armells Creek;
- STEP. Sandy-silt alluvium up to 40 feet thick occurs in the ephemeral drainage underlying the SOEP and STEP; and
- STEP Main Dam. Slightly older terrace alluvium is present in the area between Highway 39 and the STEP Main Dam.

Colluvium present in the SOEP and STEP areas are generally fine-grained unconsolidated sediments. These deposits occur at and near the land surface on hilltops, slopes and valleys.

2.1.2.2 Rosebud Coal/Clinker

This unit consists of Rosebud Coal which has been altered to clinker deposits in the SOEP and STEP areas. The extent of this unit is presented on **Figure 2-2**.

Clinker is a thermally altered rock also referred to as scoria. Clinker formed in areas where Rosebud Coal has burned, usually near where coal seams outcrop. This is most easily identified as red cap rock on hills around the region. Burning of the coal baked the overlying strata, reducing the coal volume, leaving a void for the overlying rock to collapse into or resulting in slow settling of the overlying rock into the space formerly held by the coal.

The base of the Rosebud Coal and associated clinker occurs at elevations approximately 3,380 feet above means seal level (amsl) north of the SOEP and STEP area and 3,300 feet amsl south of the SOEP and STEP. Appreciable areas of unburned Rosebud Coal were not identified by review of well logs. The clinker comprises up to 90 feet of pink to red claystone, siltstone, and fine-grained sandstone that is vesicular and fractured. In scattered areas, residual Rosebud Coal is present at the base of the clinker as ash or a combination of ash and unburned coal. It is important to note that most clinker in the SOEP and STEP areas are at an elevation above the water table and appears to be unsaturated.

2.1.2.3 Interburden

Interburden consists of siltstone, shale, and sandstone lying stratigraphically between the Rosebud and McKay Coal seams. The extent of interburden in the SOEP and STEP area is presented on **Figure 2-2**. Interburden is present to the south, west, and immediate north of the STEP, and underlies portions of the SOEP and Surge Pond. This unit has been eroded away in the East Fork Armells Creek and Stocker Creek valleys. Where present, interburden thickness is generally 10-20 feet, but in some areas (such as near well EAP 119, **Figure 2-1**) interburden thicknesses can reach 50 feet.

2.1.2.4 McKay Coal

The McKay Coal seam is 0.2 to 15 feet thick in the model area and appears to be thickest south of the SOEP and STEP and sometimes contains carbonaceous shale. The McKay Coal is not present north and west of the SOEP, north and east of the STEP, or in the floodplain of the East Fork Armells Creek due to stream erosion which has lowered the ground surface to elevations below the coal seam. The base of the McKay Coal occurs at elevations between 3,225 and 3,250 feet amsl, and represents the top of the Sub-McKay unit. The approximate extent of the McKay Coal is shown on **Figure 2-2**.

2.1.2.5 Sub-McKay Bedrock

Beneath the McKay Coal, bedrock includes interbedded and inter-fingered claystone, siltstone, fine-grained sandstone, and minor carbonaceous shale and coal stringers referred to as Sub-McKay. This unit is divided into shallow and deep zones for the purposes of describing differences in groundwater flow, but the zones have similar lithostratigraphy. The Sub-McKay unit is at least 300 feet thick, is highly layered, and is present across the entire study area. The depositional setting consisted of northeastward-flowing fluvial systems comprised of braided, meandering, and anastomosed streams. Individual bed thicknesses range from less than one foot to tens of feet.

The highly layered nature of the Sub-McKay creates considerable anisotropy between horizontal and vertical permeability. This leads to substantial vertical hydraulic gradients in the study area. The Sub-

McKay anisotropy and vertical gradients are discussed further below in **Section 2.1.4.5** and **Section 2.4.3.**

2.1.3 Hydrostratigraphic Units

Diagram 1 is a schematic showing the general hydrostratigraphy of the SOEP and STEP area. Water-bearing units in the area include alluvium, McKay Coal, and Sub-McKay sandstones and siltstones.

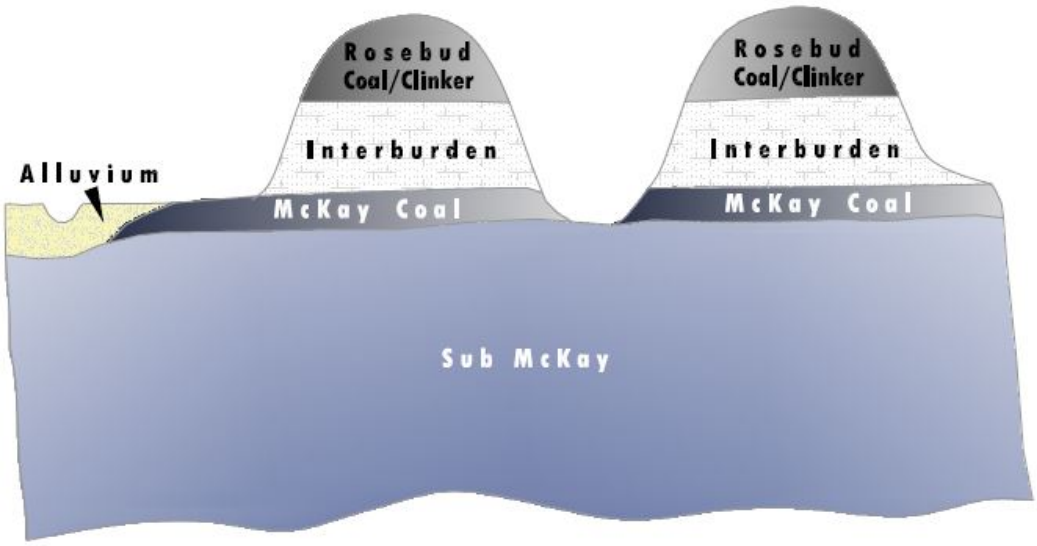

Diagram 1. General Hydrostratigraphy

Figure 2-3 shows hydrogeologic cross sections along lines A-A' and B-B', **Figure 2-4** shows hydrogeologic cross sections along line C-C' and D-D', and **Figure 2-5** shows a hydrogeologic cross-section along line E-E' (See **Figure 2-1** for cross-section line locations). As is illustrated, the relatively flat layers of overburden, Rosebud Coal, interburden, and McKay Coal have been eroded in a significant portion of the floodplain of East Fork Armells Creek. In this region, the cut valley is filled by alluvial sediments that generally coarsen with depth.

2.1.4 Hydraulic Properties

Numerous hydraulic tests have been conducted within the SOEP and STEP, Plant Site, and Townsite areas, as documented by Hydrometrics (1995), Geomatrix (2007), and NewFields (2014). **Appendix A** includes a summary of the wells tested and results of test analyses as reported in these documents.

Slug tests have been typically performed on low-yield wells. Slug test results estimate the hydraulic conductivity only for the area immediately surrounding the well, which may not be representative of the hydraulic characteristics of the aquifer beyond the immediate vicinity of the well. In addition, the accuracy of slug tests can be affected by poor hydraulic communication between the borehole wall and the surrounding formation.

Nevertheless, slug test data can be useful as a guide for estimating hydraulic conductivity in an area where pumping test data are unavailable. Transmissivity and hydraulic conductivity estimates derived

from tests of the low-yield wells were assumed to represent the magnitude and range of these parameters. A total of 19 slug tests have been performed to date at wells in the SOEP and STEP areas (**Appendix A**).

Pumping tests typically provide for a better understanding of hydraulic conductivity than slug tests because these tests are longer in duration and stress a larger portion of the aquifer and in many cases water levels are monitored both in the pumping well and associated observation wells. Drawdown in observation wells provide more accurate information on the transmissivity of the water bearing units between the pumping and observation wells. A total of 51 pumping tests have been performed to date in the SOEP and STEP areas (**Appendix A**).

Table 2-1 summarizes the range and central tendencies of transmissivity and hydraulic conductivity estimates of the various hydrostratigraphic units, based on hydraulic tests conducted in over 90 wells in the SOEP and STEP, Plant Site, and Townsite areas**.** **Table 2-1** also includes ranges of aquifer properties documented in referenced peer-reviewed studies of the Fort Union Formation. The following subsections discuss hydraulic characteristics of the major hydrostratigraphic units.

Table 2-1. Summary of Aquifer Properties by Hydrostratigraphic Unit.

Aquifer Properties from SOEP, STEP, Plant Site, and Colstrip Townsite areas						
Hydro-Stratigraphic Unit	Geometric Mean Transmissivity (feet^2/day)	Geometric Mean Hydraulic Conductivity (feet/day)	Minimum Hydraulic Conductivity (feet/day)	Maximum Hydraulic Conductivity (feet/day)	Geometric Mean Saturated Thickness (feet)	Geometric Mean Storativity
Alluvium	225	18.3	0.15	355	12	0.0003
Rosebud	149	12.5	0.9	65	12	N/A
Interburden	13	1.1	0.02	39	13	N/A
McKay	26	2.3	0.06	9.3	10	N/A
Sub-McKay	41.5	2.5	0.03	242	14.1	0.0008

Aquifer Properties from Studies[1] of the Fort Union Formation			
Hydro-Stratigraphic Unit	Transmissivity (feet^2/day)	Hydraulic Conductivity Range (feet/day)	Storage Coefficient
Alluvium	1,900	0.00007 – 492	--
Rosebud	1.3 – 1,700	0.1 – 68	--
Interburden	28	0.9	--
McKay	0.7 – 31	0.01 – 3.1	--
Sub-McKay[2]	0.7 – 31	0.01 – 3.1	--

N/A – not applicable
"--" – no data available.
1 – Rehm et al. (1980), Van Voast and Reiten (1988), and Van Voast et al. (1977).
2 - Assumes same values as McKay Hydrostratigraphic Unit.

2.1.4.1 Alluvium

Hydraulic conductivity estimates for alluvium range from 0.15 up to 355 feet/day with a geometric mean of 18.3 feet/day. The lower values are associated with the fine-grained alluvial sediments, while higher values are associated with the sand and gravel deposits. As described previously, the alluvial unit tends

to coarsen with depth from fine-grained silt and clay deposits to underlying sand and gravel. Aquifer tests in the sand and gravel unit had semi-confined to confined responses with a geometric mean storativity of 0.0003.

Hydraulic conductivity estimates for alluvium east of the STEP Main Dam range from 2.1 to 355 feet/day at wells 377A, 378A, 382A, 908A 910A, 985A, 997A, 998A, 2013A 2035A and 2038A. Slug test results from well 2017A, completed in thinly saturated alluvium and approximately 4.5 feet of bedrock, range from 1.0 to 1.6 feet/day. West of the Surge Pond alluvium hydraulic conductivity is estimated to be 2.4 feet/day at 977A. Hydraulic conductivity estimates for alluvium beneath the SOEP range from 2.8 to 7.2 feet/day at 2001A. Hydraulic conductivity estimates for alluvium beneath the STEP range from 1 to 2 feet/day based on tests in wells 921A, 923A and 924A.

2.1.4.2 Rosebud Coal/Clinker

Hydraulic conductivity estimates for Rosebud Coal range from 0.9 to 65 feet/day with a geometric mean of 12.5 feet/day (**Table 2-1**). Clinker permeability varies but is typically relatively high, with the actual value dependent on the amount of fine-grained sediments that have moved vertically into the available pore spaces within the unit and the degree and nature of fracturing present. Typically, however, clinker is present above the water table in the SOEP and STEP areas. The enhanced permeability of this unit at the surface or near-surface generally serves to create areas of relatively high net recharge to groundwater.

2.1.4.3 Interburden

The measured hydraulic conductivity of interburden ranges from 0.02 to 39 feet/day with a geometric mean of 1.1 feet/day. The higher end values (6.8 to 39 feet/day) occurred in tests conducted in areas where the overlying bedrock has eroded, likely resulting in partial weathering of the interburden unit. Hydraulic conductivity for wells screened in interburden that was not exposed to weathering range from 0.02 to 0.04 feet/day. Hydraulic conductivity estimates for interburden wells west of the Surge Pond range from 0.7 to 0.9 feet/day as reported for 978S and 979S.

2.1.4.4 McKay Coal

The McKay Coal unit exhibits slightly lower permeability than the Rosebud Coal. The hydraulic conductivity in the McKay Coal ranges from 0.06 to 9.3 feet/day, with a geometric mean of 2.3 feet/day.

2.1.4.5 Sub-McKay

Hydraulic conductivity estimates for siltstone and sandstone of the Sub-McKay unit range from 0.03 to 242 feet/day with a geometric mean of 2.5 feet/day. Due to the dip of the Fort Union Formation, the Sub-McKay unit is present near ground surface near the SOEP and STEP. Most of the wells yielding higher permeability are in locations where the Sub-McKay is present at shallower depths. The relatively higher permeability values measured at these locations are likely due to increased fracturing. This unit generally behaves as a semi-confined aquifer and has a geometric mean storativity of 0.0008.

East of the STEP Main Dam, horizontal hydraulic conductivity values for bedrock wells 983D, 984D, 988D, 989D, 2003D, 2005D, 2006D, 2008D, and 2012D were estimated to be 11 to 357 feet/day. These values are relatively high for Tongue River Member bedrock and likely indicate the presence of conductive fractures in the areas around these wells. Hydraulic conductivity estimates of this magnitude

in bedrock were found only in this area. Other bedrock wells east of the STEP Main Dam (379D, 380D, 387D, 904D, 905D, 906D, 927D, 981D, 982D, 986D, 987D, 996D, 999D, 2000D, 2004D, and 2007D) have estimates of hydraulic conductivity that range from 0.03 to 5.7 feet/day. Beneath the STEP ponds, hydraulic conductivity of the Sub-McKay at well 958D is estimated at 2 feet/day. North of the STEP ponds, hydraulic conductivity values for bedrock wells 2009D, 2010D, 2011D, 2022D and 2023D are estimated to be 0.1 to 1.0 feet/day. North of SOEP hydraulic conductivity for Sub-McKay wells 367D, 903D, 2024 D, 2025D, 2026D, and 2031D are estimated to range from 0.8 to 8 feet/day. West of the SOEP hydraulic conductivity for Sub-McKay wells 369D, through 373D are estimated to range from 0.2 to 1.2 feet/day. North of the Surge Pond hydraulic conductivity values for Sub-McKay Wells 364D, 368D and 384D are estimated between 0.1 and 0.7 feet/day.

Sub-McKay bedrock is a highly layered sequence of sandstone lenses inter-fingered with shale, claystone and siltstone, which creates substantial anisotropy between horizontal and vertical hydraulic conductivity. Relatively high permeability sandstone layers and lenses are often interbedded with very low permeability siltstone/claystone layers with hydraulic conductivity values that can be six or seven orders of magnitude lower than sandstone layers. Some claystone units are so low in permeability that they will not yield water when drilled through and appear to be dry.

Infiltrating recharge (both natural and from impoundments) migrates readily through the more permeable sandstone beds but is inhibited in its vertical migration by low permeability layers (except where vertical fractures are present). In the SOEP and STEP area, this often results in large vertical gradients where hydraulic head (groundwater elevations) in deep Sub-McKay wells is often much lower than in shallower Sub-McKay wells.

Due to contrasting permeability, groundwater flow in the Sub-McKay is greater in sandstone layers relative to finer-grained bedrock (siltstone/sandstone/shale) layers. Potential preferential groundwater flow paths are discussed below in **Section 2.4.2**. Where no information is available indicating the presence of fractures, flow in this unit is assumed to be horizontally isotropic within sandstone and siltstone layers.

2.2 PRECIPITATION

The climate in Colstrip, Montana is considered semi-arid with an average annual precipitation, based on 78 years of site data from the Western Regional Climate Center (2015), of 15.20 inches (**Table 2-2** and **Appendix B**). The data are from 1927 to 2014, excluding years with missing monthly data.

Figure 2-6 presents the average monthly precipitation for the period of record along with the 2005, 2006, 2007, and 2014 monthly precipitation totals (these years were selected because they correspond to periods for model calibration described below in **Section 4.0**). Most precipitation occurs between the months of April and October during which, on average, it exceeds one-inch for each of these months. Precipitation typically peaks in the months of May and June, during which average precipitation exceeds 2.6 inches for both months.

The average annual precipitation has varied over the last 40 years, a period that coincides with the approximate life of the SOEP and STEP. **Figure 2-7** presents the annual total precipitation as a variance from the average of 15.2 inches. In general, the 1980s, the 1990s, and the early 2000s all had average to below average precipitation. Conversely, since 2005, precipitation at Colstrip has generally been above average. In particular, measured annual precipitation during calendar years 2005, 2011 and 2013

exceeded the average by more than 8 inches, while precipitation in 2014 exceeded the average by about 4 inches.

Table 2-2. Average Monthly Precipitation

Month	Average Monthly Precipitation*
January	0.60
February	0.55
March	0.92
April	1.61
May	2.67
June	2.66
July	1.29
August	1.16
September	1.25
October	1.27
November	0.64
December	0.57
Total	15.20

*Data from Western Regional Climate Center (Appendix B). Averages include period of record through 1927-2014.

2.3 SURFACE WATER HYDROLOGY

Several surface water features exist in the area near the SOEP and STEP. These include:

- East Fork Armells Creek;
- Castle Rock Lake (Surge Pond);
- SOEP (reclaimed but historically was an artificial fly ash pond surface water feature);
- STEP Area;
- Golf Course irrigation Pond; and
- Stocker Creek.

These surface water features are shown on **Figure 1-1, Figure 1-2,** and **Figure 2-1** and are discussed below. **Figure 1-1** also shows the locations of drainage basin boundaries.

2.3.1 East Fork Armells Creek

The primary drainage in the area is the East Fork Armells Creek, which drains the SOEP and STEP area as well as the Townsite, the western half of the Plant Site area and portions of Rosebud Mine south and west of the SOEP (**Figure 1-1**). The drainage divide between the East Fork Armells Creek and Stocker Creek runs from southwest to northeast about 500 to 1000 feet northwest of the SOEP and STEP (**Figure 1-1**).

The drainage divide between East Fork Armells Creek and Stocker Creek does not represent a groundwater divide. Groundwater flow is often parallel to topography because recharge is commonly greatest along ridgetops, creating groundwater divides beneath the topographic divides. This is not always the case however, particularly where sources of artificial recharge are present. At the SOEP and STEP area, the greatest sources of recharge to groundwater are seepage form the Surge Pond, SOEP,

and STEP. For this reason, the East Fork Armells Creek/Stocker Creek divide is not coincident with a groundwater flow divide. Groundwater flow is discussed further in **Section 2.4**.

Seventeen synoptic runs have been conducted on the East Fork Armells Creek since 1993 (Hydrometrics 2001, 2007, 2010, 2012, 2014, and 2016) at the gaging stations shown on **Figure 2-1**. **Table 2-3** summarizes the flow measurements for East Fork Armells Creek for stations within the SOEP and STEP area, which are shown graphically by distance downstream for each event on **Figure 2-8**. The uppermost station on the creek is AR-12, located near the Plant Site, and the distances downstream listed for each station are measured from AR-12. There are three additional stations in the Plant Site area upstream of AR-2 (also referred to as the South Flume).

Most of the synoptic flow measuring events were conducted between mid-March and mid-June, with the exception of the October 2014 event. Data indicate that the creek generally gains flow from groundwater recharge along most reaches within the model area.

Synoptic flow data indicate East Fork Armells Creek consistently loses flow to groundwater between stations AR-1 and AR-9 (202 gallons per minute [gpm] loss on average). Several reaches intermittently vary from gaining to losing; this includes the reach between AR-9 and AR-8, the reach between AR-8 and AR-7, the reach between AR-7 and AR-6 and the reach between AR-11 and AR-10. These sites extend from just northeast of the Surge Pond through the golf course. In addition, AR-7 lies just below the irrigation holding pond, which holds treated sewage water from the water treatment plant. The first reach may not be representative because the flume at AR-1 may yield erroneous flow measurements at higher flows due to submergent conditions (Hydrometrics, 2015b). The extreme flow measurement at AR-7 on April 5, 2011 appears anomalous, but was used in the calculation of the geometric mean.

Table 2-3. Flow Measurements for East Fork Armells Creek-SOEP and STEP Area

Station	AR-2	AR-1	AR-9	AR-8	AR-7	AR-6	AR-11	PBR-AR10
Distance Downstream*	6,419	10,662	12,435	13,554	14,471	16,016	17,526	18,223
Date	**Flow (gpm)**							
3/19/15	673	1,135	678	606	669	664	727	754
10/16/2014	171	300	167	60	103	163	180	224
4/8/2014	498	1,176	539	673	669	808	875	1,070
3/20/2013	274	938	180	162	413	278	355	231
3/21/2012	190	1,042	412	512	358	449	467	286
4/5/2011	296	768	895	371	1,089	448	740	410
3/30/2010	229	368	213	192	208	325	303	213
4/8/2009	296	525	310	359	369	358	400	192
4/3/2008	219	319	193	241	238	274	291	377
5/14/2007	417	835	762	485	569	579	662	705
5/27/2005	395	736	561	509	492	460	502	576
6/16/2004	134	346	223	146	106	197	198	260
5/21/2003	319	705	390	395	404	453	489	1,306
4/25/2000	230	368	465	424	396	507	----	708
4/15/1996	417	471	----	----	----	----	----	----
3/17/1994	368	471	----	----	----	----	----	----
6/15/1993	346	395	----	----	----	----	----	----
Average Flow	322	641	428	367	435	426	476	522
GEOMEAN	298	578	370	310	361	390	428	430
Gain/loss (Ave)	185	319	-255	-61	68	-9	56	32
Max	673	1,176	895	673	1,089	808	875	1,306
Min	134	300	167	60	103	163	180	192

Notes: * distance in feet downstream from site AR-12 (uppermost gage on the East Fork Armells Creek); --- not measured

2.3.2 Castle Rock Lake (Surge Pond)

Castle Rock Lake, known as the Surge Pond, is an approximately 150-acre constructed impoundment that was built in 1974 to store water to be used for the coal-fired steam electric plant. The impoundment was constructed in a small drainage that was tributary to East Fork Armells Creek. The lake elevation is maintained by inflow from a pipeline that routes water from the Yellowstone River. The stage in the Surge Pond has varied by up to 10 feet (between 3,274 and 3,284 feet amsl; **Appendix C**), but the typical annual variation is 4 feet (from 3,279.5 to 3,283.5 feet amsl). The impoundment appears to be a flow-through lake with the groundwater elevations slightly above lake levels west of the lake and groundwater elevations below lake level north, east and south of the lake.

2.3.3 SOEP Area

The SOEP was operated between 1975 and 1997 and was constructed with a partial liner consisting of natural clay. During operation, fly ash slurry was pumped from the Plant Site into the pond through a fiberglass pipeline. Fly ash settled in the pond and the water was periodically pumped back to the Plant Site for use as process water. The pond was determined to be full in 1997 and was reclaimed in 2002.

2.3.4 STEP Area

The STEP consists of five cells that are lined with either high density polyethylene (HDPE) or reinforced polypropylene (RPP). These cells consist of the following:

- Cell A;
- Cell B (New Clearwell);
- Cell D;
- Cell E; and
- Old Clearwell.

Fly ash contained in scrubber slurry from Units 1 and 2 is currently pumped in a pipeline to the STEP Paste Plant which was constructed south of Cell A in 2009. The Paste Plant removes excess water from the scrubber slurry. This process increases the solids of the scrubber slurry from about 15 percent to about 65 percent. The paste is currently transported by pipeline to Cell E and the Old Clearwell, where it hardens to a concrete-like material that helps reduce seepage.

Cell A was constructed with single High Density Polyethylene (HDPE) liner and originally received scrubber slurry. Cell A is full and no longer receives fly ash or water from capture systems or the passive evaporation system formerly located at the northwest corner (**Figure 2-1**). The passive evaporation system was removed in 2015.

Cell B, also known as the New Clearwell, was constructed in 2006 and includes a double-lined RPP and a leachate collection system. It was operated as a secondary decant pond between 2006 and 2011. In 2011 it was converted to the New Clearwell, and receives clear water from the paste plant for return to the scrubbers for reuse. This cell still contains fly ash decanted between 2006 and 2011.

Cell D was constructed in 2011 and is currently used for water management. This cell was constructed with double-lined RPP and a leachate collection system.

Cell E is an active cell that was constructed with a composite liner. It originally received decant water from Cell A. Pasting of Cell E began in 2009, and a large portion of E cell has been filled with paste thereby reducing potential seepage.

The Old Clearwell is currently used for water storage and will be filled with paste (Hydrometrics, 2016). In April 2007, the liner along the southern edge of the Old Clearwell was torn when struck by a barge (Hydrometrics, 2015b). Repairs to the Clearwell liner were completed in November 2007. Well 955D was installed to capture this seepage. Well 955D was subsequently abandoned prior to construction of Cell D and replaced with capture well 2019D.

2.3.5 Stocker Creek

Stocker Creek lies to the northwest of the SOEP and STEP (**Figure 1-2**) and flows from the southwest to the northeast. Stocker creek drains portions of the Rosebud Mine west of the SOEP as well as slopes north of the SOEP and STEP beyond the East Fork Armells Creek/Stocker Creek divide eventually discharging to East Fork Armells Creek. Data regarding flow in Stocker Creek are limited. Based on review of aerial photography of the area taken between 1993 and 2014, flow in Stocker Creek appears to be ephemeral or intermittent. The lowest reach of Stocker Creek near the confluence with East Fork Armells Creek contains water more often than reaches above it.

2.4 GROUNDWATER FLOW

Groundwater flow in the area surrounding the SOEP and STEP is generally from southwest to northeast (see **Figure 2-9** through **Figure 2-14**). Locally, flow directions and gradients are influenced by surface water in the area, including the Surge Pond, the STEP, and East Fork Armells Creek. Pumping of capture wells also influences local gradients and groundwater flow direction.

East Fork Armells Creek and Stocker Creek and associated alluvium influence shallow groundwater flow in the SOEP and STEP areas. The ancestral East Fork Armells Creek eroded through shallow bedrock (overburden, interburden and Rosebud and McKay Coal), and in some places, into the Sub-McKay deposits. In the SOEP and STEP area, overburden is not present and the Rosebud coal (as Clinker deposits) is not saturated. Groundwater in the interburden (where saturated), McKay Coal and Sub-McKay mostly flows towards East Fork Armells Creek. Groundwater in Sub-McKay bedrock immediately north of the SOEP and STEP flows north and then northeast. Groundwater originating from the SOEP and STEP that is flowing east is being captured by wells prior to reaching alluvium associated with the creek. The direction of groundwater flow in alluvium along the creek is generally north-northwest parallel to the creek. Groundwater flows east and northeast from the Surge Pond and some of this water flows into alluvium along East Fork Armells Creek. Interaction between surface water and groundwater in East Fork Armells Creek controls groundwater elevations along the creek. Although Stocker Creek is an intermittent stream, alluvium beneath this creek provides a drain for shallow bedrock groundwater in the area.

2.4.1 Potentiometric Surfaces

Potentiometric surface maps were constructed using groundwater elevations primarily from Talen's water level data base, augmented with data obtained by Montana Bureau of Mines and Geology Groundwater Information Center (GWIC, 2016) and Western Energy (2013f) to provide greater spatial coverage. Data used to create potentiometric surface maps are contained in **Appendix D**. Groundwater elevations measured at pumping wells identified in the appendix represent pumping water levels in those wells at the time of measurement.

The modeling analysis discussed later in this document focuses on groundwater conditions between 2005 and 2014. Two sets of potentiometric surface maps were created to represent conditions at the beginning and end of this period. These maps are used in evaluating steady-state model calibration (described in **Section 4.0** below). Groundwater data used to construct the maps was selected to represent winter conditions when seasonal aquifer stresses are at a minimum and are most representative of steady-state conditions.

The majority of water levels used to create the potentiometric maps were measured in October 2005 and October 2014. However, as discussed below, some water levels were used that were measured at times other than October 2005 and October 2014. This was necessary to provide spatial coverage. Well hydrographs were reviewed and it was concluded that water levels measured within two years of October 2005 and October 2014 vary by less than 1 or 2 feet. While using non-October water levels may introduce some uncertainty, an inspection of the potentiometric maps indicates that using water levels in the observed range would not change the groundwater flow directions or gradients depicted on these maps appreciably.

The first set of potentiometric surface maps represent flow conditions in late 2005 for the shallow groundwater systems (includes alluvium, interburden, McKay Coal, and shallow Sub-McKay), the middle Sub-McKay, and a deeper component of the Sub-McKay (**Figure 2-9** through **Figure 2-11,** respectively). Groundwater elevation data illustrated on **Figure 2-9** through **Figure 2-11** include symbols that indicate when the water levels were measured. The 2005 Shallow and mid Sub-McKay potentiometric maps were prepared with groundwater elevations measured in October 2005. For some areas of the Deep Sub-McKay map, water levels measured prior to October 2005 were used to provide additional spatial coverage in areas where October 2005 data were not available. In addition, data for several wells on the edge or outside of the SOEP and STEP areas were obtained from other sources including the Montana Bureau of Mines and Geology Groundwater Information Center (GWIC, 2016) and Rosebud Mine (Western Energy, 2013f). These data were included to provide a conceptual overview of flow direction and gradient near and outside of model boundaries (discussed in **Section 3.3** below).

The second set of potentiometric surface maps represents groundwater conditions in late 2014 for these same units (**Figure 2-12** through **Figure 2-14**). Groundwater elevation data illustrated on **Figure 2-12** through **Figure 2-14** include symbols that indicate when the water levels were measured. The 2014 potentiometric maps were created using groundwater elevation data measured in Talen monitoring wells in October 2014, where available. Groundwater elevations measured prior to October 2014 were used in a few areas to provide spatial coverage where October 2014 data were not available. In addition, data for several wells on the edge or outside of the SOEP and STEP areas were obtained from other sources including the Montana Bureau of Mines and Geology Groundwater

Information Center (GWIC, 2016) and Rosebud Mine (Western Energy, 2013f). These data were included to provide a conceptual overview of flow direction and gradient near and outside of model boundaries (discussed in **Section 3.3** below).

Potentiometric maps were created for the shallow groundwater flow system, the mid Sub-McKay and the deep Sub-McKay. The shallow flow system is generally defined as the hydrostratigraphic package that the alluvial system cuts through and is comprised of alluvium, interburden, McKay Coal and the shallowest Sub-McKay (upper 40 to 75 feet below the McKay). The mid Sub-McKay is generally between 75 feet below the contact with McKay Coal and 250 feet below the McKay Coal. The deep Sub-McKay Unit is generally greater than 250 feet below the McKay Coal or at elevations below 3,100 feet amsl. Flow in the mid Sub-McKay unit more closely resembles shallow flow directions and gradients observed in shallow system while flow in the deep Sub-McKay exhibits a more regional pattern.

Shallow groundwater flow within and near the SOEP and STEP area (**Figure 2-9** and **Figure 2-12**) is generally to the north/northeast. Along both East Fork Armells Creek and Stocker Creek groundwater flow converges into the alluvium. Shallow groundwater flow is also influenced by the Surge Pond, the STEP, and by capture well pumping. Groundwater flows towards the Surge Pond from the southwest and away from the pond to the northeast. Downgradient (northeast) of the Surge Pond, the groundwater gradient is much steeper than upgradient (southwest) of the pond indicative of seepage from the pond. Drawdown from capture well pumping is evident in the shallow system (**Figure 2-12**) as cones of depression north of the SOEP, west of Cell A, and east of the STEP Main Dam.

Figure 2-10 and **Figure 2-13** are potentiometric maps for the mid Sub-McKay in 2005 and 2014, respectively. The groundwater flow in this unit reflects similar characteristics of the shallow flow system. Flow in the mid Sub-McKay is generally to the north/northeast and locally toward East Fork Armells Creek and Stocker Creek. Cones of depression due to capture well pumping are evident in the mid Sub-McKay west of Cell A and east of the STEP Main Dam (**Figure 2-13**).

Figure 2-11 and **Figure 2-14** are potentiometric maps for the Deep Sub-McKay in 2005 and 2014, respectively. These maps were created using groundwater elevation data measured in wells screened in the deep Sub-McKay unit at elevations below 3,100 feet amsl. Groundwater elevation data available for this interval are limited. Groundwater flow at this depth is notably different than in shallower units. Flow is generally to the east-northeast toward the lower reach of Rosebud Creek and Yellowstone River, which are thought to be regional discharge points for the deep regional groundwater flow system. Groundwater elevations in deep wells are generally greater than 70 feet lower than overlying water table elevations, indicating downward hydraulic gradients exist between the shallow and deep flow systems across the study area.

Figures 2-9 through **2-14** show the location of a groundwater divide that runs beneath the middle of the Surge Pond and a drainage downgradient of the Surge Pond Main Dam. This divide follows streamlines in the potentiometric surfaces**.** A streamline is a line perpendicular to equipotential lines and parallel to groundwater flow, so by definition, no groundwater crosses a streamline. This implies that no groundwater from the SOEP and STEP area flows across this boundary, so groundwater north of the Surge Pond remains north of this divide and groundwater south of Surge Pond remains south of this divide.

2.4.2 Preferential Flow

Groundwater flow may be influenced by the presence of joints and fractures as well as stratigraphy. Stratigraphy has the greatest influence on preferential flow of groundwater. Groundwater preferentially moves through more permeable sand and gravel in alluvium and sandstone layers and lenses in bedrock relative to less permeable alluvial silt and siltstone, claystone and shale. As sandstone lenses pinch out, groundwater flow can be diverted laterally. Data from several investigation have helped evaluate the presence of potential preferential flow paths. Laterally extensive fractures sets have not been identified.

Maxim (2004) suggested a preferential pathway for transport of constituents may exist south of the STEP area related to fracturing in sandstone near the south end of the STEP Main Dam. Shallow Sub-McKay sandstone near wells 380D, 383D, and 393D (located south of the STEP area) has elevated constituent concentrations that Maxim (2004) concluded may originate from the Stage II Ponds. The Sub-McKay sandstone unit in this area may extend below the elevation of the grout curtain associated with the Stage II Dam (cross-section A-A', **Figure 2-3**). Wells 380D, 383D, and 393D were converted to groundwater recovery wells in an attempt to intercept impacted water in this zone.

In 2005, Hydrometrics installed wells 960D, 961D, 962D, 963D, 964D, 965D, 968D, 969D, 970D, and 971D along the east flank of the STEP dam as potential capture wells. Previous groundwater modeling completed by Maxim (2005) had suggested that a series of capture wells screened from the water table down to an elevation of approximately 3,100 feet amsl immediately downgradient (east) of the STEP dam would be effective in capturing groundwater flowing beneath the dam that was impacted by process pond water.

Hydrometrics (2007) completed aquifer tests on wells 960D, 961D, 962D, 963D, 964D and 965D with multiple observation wells documenting drawdown and the degree of lateral hydraulic communication between wells to help evaluate the effectiveness of each potential capture well. Testing results help identify potential preferential pathways. **Figure 2-1** shows well locations and cross section A-A' on **Figure 2-3** shows the screened intervals for the test and observation wells relative to stratigraphy. During pumping of well 960D, more than a foot of drawdown was observed in well 961D located 185 feet north of the pumping well and negligible drawdown was observed in well 395D located about 220 feet south of the pumping well. This anisotropic response to pumping is likely due to the fact that wells 960D and 961D are both screened across a sandstone layer between elevation of approximately 3,015 and 3,025 feet amsl. Well 385D does not intercept the same sandstone layer. During the pumping test on well 961D, wells 960D and 962D (located 185 feet south and 250 feet north of the pumping well, respectively) exhibited generally isotropic drawdown responses to pumping. During a pumping test on well 962D, wells 961D and 963D (located about 180 feet south and 260 feet north of the pumping well, respectively) exhibited fairly isotropic drawdown responses to pumping.

There is evidence that a relatively thick continuous zone of sandstone with elevated permeability, present in mid-level Sub-McKay between the center of the STEP and wells north of there, is in direct hydraulic communication that could serve as a preferential flow path. Well 958D (located beneath the center of the STEP) was converted to a capture will in 2010. As is discussed further in **Section 2.4.7,** when pumping was initiated, drawdown was observed in wells 902D and 975D north of the STEP. Subsequently, as pumping rates in 958D were increased and decreased, water levels in deeper wells (2009D, 2010D, and 2011D) north of 958D responded to the pumping changes. Drawdown was not observed on other wells in the area.

2.4.3 Horizontal Gradients

Horizontal hydraulic gradients in shallow groundwater are variable with the steepest gradients (up to 0.10) occurring in the shallow units existing below the Surge Pond and below the STEP Main Dam (**Figure 2-9** and **Figure 2-12**). The flattest gradients (0.002) occur west of the Surge Pond and SOEP, to the east of East Fork Armells Creek, and in the northwest portion of the area near Stocker Creek. The remaining areas have horizontal gradients that generally range between 0.006 and 0.017.

Most gradients in the mid Sub-McKay intervals are within the range noted for the shallow units, although immediately below the STEP Main Dam gradients are much steeper due to pumping influences. Horizontal gradients in the deep Sub-McKay groundwater are less influenced by the creek, pond seepage, and capture system pumping. Horizontal gradients in the deep Sub-McKay unit range from 0.004 to 0.008.

2.4.4 Vertical Gradients

Figure 2-15 illustrates vertical gradients calculated from water levels measured in paired wells[1]. The vertical gradients are also summarized in **Table 2-4**. Data used to calculate vertical gradients (screen and groundwater elevations) are included in **Table E-1** in **Appendix E** along with diagrams illustrating the relative depths of screens and units for the well pairs (**Figure E-1-1** through **Figure E-1-7**).

Vertical gradients calculated from water level measurements at well pairs are exclusively downward across the site. Relatively strong downward gradients were measured to the east of the Surge Pond at well pair PZ12C/PZ12D (downward gradient of 1.03), to the northwest of the ponds in the Sub-McKay at well pair 398D/399D (downward gradient of 0.82), and near the SOEP area in the Sub-McKay at well pair 2031D/2025D (downward gradient of 0.75). Vertical gradients are smallest south of SOEP in well pairs 374S/979S and 389A-P/390D-P (downward gradients of 0.08 for both pairs), and in the deep Sub-McKay north of the SOEP in well pair 2025D/2026D (downward gradient of 0.05).

Well pair 967P and 946 indicate a downward gradient between fly ash in the SOEP and underlying alluvium. This is further illustrated on **Figure E-1-8** in **Appendix E** by a hydrograph of these two wells along with other wells in the vicinity (947, 2002A, 2001A, and 966A). A diagram (**Figure E-1-7**) showing the relative depths of the screens in these wells and the fly ash-alluvium contact is also included in **Appendix E**. Since the SOEP was capped, water in the fly ash has been draining into the underlying alluvium, a process enhanced by pumping at 966A. The hydrograph of this group of wells shows a consistent downward gradient from the shallowest well (947 in the fly ash) to 967P (mostly in fly ash) then to 2002A and 2001A (both screened across the fly ash and alluvium) and to 946 (also screened across the fly ash and alluvium) and then to 966A (screened solely in the alluvium). The hydrograph also suggests that all of the wells are being influenced by pumping at 966A. However, 966A pumping has been constant since 2006 with only a few short-term changes, as shown on the hydrograph, so the downward vertical gradient indicated by this cluster of wells is representative of conditions for the past seven years.

1 Well pairs include multiple wells, completed at different depths. Well pairs in which one well is a capture well were excluded from this analysis.

Table 2-4. Vertical Gradient Summary

Well Pair	Upper Hydrostratigraphic Unit	Lower Hydrostratigraphic Unit	Gradient	Direction	Date
South of SOEP					
374S/979S	Rosebud/Clinker	Sub-McKay	0.08	Down	10/8/2014
389A-P/390D-P	Interburden	Sub-McKay	0.08	Down	10/8/2014
East of Surge Pond					
PZ10S/PZ10D	Unknown	Sub-McKay	0.31	Down	10/23/2012
PZ12S/PZ12C	Sub-McKay	Unknown	0.67	Down	10/2/2013
PZ12C/PZ12D	Unknown	Unknown	1.03	Down	10/2/2013
Southeast of STEP Old Clearwell					
2006D/2005D	Sub-McKay	Sub-McKay	0.09	Down	10/7/2014
998A/999D	Alluvium	Sub-McKay	0.13	Down	9/4/2008
997A/996D	Alluvium	Sub-McKay	0.50	Down	9/4/2008
994A/993D	Alluvium	Sub-McKay	0.50	Down	8/5/2008
991A/990D	Alluvium	Sub-McKay	0.49	Down	8/5/2008
Below Main Step Dam and East Fork Armells Creek					
360A/359D	Alluvium	Sub-McKay	0.13	Down	10/8/2014
918A/919D	Alluvium	Sub-McKay	0.25	Down	10/7/2014
North of STEP					
901D/900D	Sub-McKay	Sub-McKay	0.41	Down	10/7/2014
398D/399D	Sub-McKay	Sub-McKay	0.82	Down	5/2/2014
399D/397D	Sub-McKay	Sub-McKay	0.27	Down	5/2/2014
SOEP and North of SOEP					
2031D/2025D	Sub-McKay	Sub-McKay	0.75	Down	10/7/2014
2025D/2026D	Sub-McKay	Sub-McKay	0.05	Down	10/7/2014
967P/946	Fly Ash	Fly Ash/Alluvium	0.47	Down	10/8/2014

Notes:
Gradients generally calculated using October 2014 water level measurements. Except as follows:
-398D/399D and 399D/397D calculated using May 2014 water level data,
-PZ10S/PZ10D calculated using October 2012 water level data,
-PZ12S/PZ12C and PZ12C/PZ12D calculated using October 2013 water level data, and
-998A/999D, 997A/996D, 994A/993D, and 991A/990D calculated using Sept. and Aug. 2008 water level data.

2.4.5 Variability of Vertical Gradients

Figure 2-16 and **Figure 2-17** are hydrographs for several paired wells organized by location in the SOEP and STEP. These figures show that downward gradients have been consistently present through time at nearly all well pairs. Diagrams are included in **Appendix E** illustrating the relative screen depths and lithology for the wells shown on the hydrographs.

South of the SOEP (**Figure 2-17**), well pair 374S/979S generally exhibited downward gradients between 2008 and 2015. During 2008, 2009, 2010, 2011, and 2014, the vertical gradient reversed in this well pair sometime between January and March. Well pair 389A-P/390D-P exhibits appreciable downward gradients between 2006 and 2015. These wells are completed in alluvium/interburden and Sub-McKay intervals, respectively. Groundwater elevations in wells 389A-P and 390D-P fluctuated between mid-2012 through December 2015. Groundwater elevation fluctuations appear to be partly due to changes in pumping rates at the nearby capture well EAP-119, although responses are not identical. A hydrograph for EAP-119 is presented and discussed below in **Section 2.4.6**.

Well pair PZ10S and PZ10D (located east of the surge pond, **Figure 2-17**) exhibited an upward vertical gradient for measurements between June 2008 and June 2012. Except for a measurement in April 2013, the vertical gradient between these wells was downward between July 2012 and December 2013. The reason for the change in vertical gradients for PZ10S/PZ10D is unclear and is not consistent with nearby well triplet PZ12S/PZ12C/PZ12D. Vertical gradients were consistently downward between 2008 and 2014 in tripled wells PZ12S, PZ12C, and PZ12D. These two sets of well are located on opposite sides of the drainage downgradient (east) of the Surge Pond main dam.

Southeast of the Old Clearwell (**Figure 2-16** and **Figure 2-17**), well pair 2006D/2005D exhibited a consistently downward gradient between 2010 and 2015 (**Figure 2-17**). Alluvial capture well 998A is paired with Sub-McKay well 999D (**Figure 2-17**). This pair generally exhibits a downward gradient, whether well 998A is pumping or not. The one exception is a brief reversal in gradient during early June 2011. Alluvial wells 997A and 994A are paired with Sub-McKay wells 996D and 993D, respectively (**Figure 2-17**). All of these wells except 996D are capture wells and both pair's exhibit consistently downward gradients during both pumping and non-pumping conditions. Well 991D is a capture well that is paired with deeper well 990D (**Figure 2-16**). This pair has generally exhibited a downward gradient during both pumping and non-pumping conditions except for during 2010, when the pumping rate in well 991D was increased, reversing the gradient to upward.

Well pairs completed in the drainage east of the STEP Main Dam (360A/359D) and in East Fork Armells Creek alluvium (918A/919D) have exhibited consistently downward gradients (**Figure 2-16**). North of the STEP (**Figure 2-16**), well pair 901D/900D and triplet wells (398D/399D/397D) have exhibited consistently downward gradients.

Within the reclaimed SOEP area, three wells are completed adjacent to each other: 967P is screened near the water table in SOEP fly ash, 946 is screened at the interface between fly ash and bedrock, and 966A is a capture well screened in alluvium next to well 946 just below the fly ash (**Figure 2-16**). In general, gradients are downward from shallow fly ash into underlying deeper fly ash/bedrock and alluvium under both pumping and non-pumping conditions; however there have been brief periods in 2009 and 2012 when well 966A was not pumping that gradients were upward from the alluvium to overlying fly ash. The relationship of 967P, 946, and other wells in the area to pumping at 966A was discussed above and is illustrated on **Figure E-1-7** and **Figure E-1-8**. Because 966A pumping has been pumping constantly since 2006 with only a few short-term changes, the downward vertical gradient indicated by this cluster of wells is representative of conditions for the past seven years.

North of the SOEP triplet wells 2031D/2025D/2026D are screened at different depths in the Sub-McKay. Well pair 2031D/2025D has consistently exhibited a downward gradient since 2013 when well 2031D was installed (**Figure 2-16**). The deeper paired wells 2025D and 2026D (**Figure 2-16**) displayed minimal vertical gradient for the first several month after they were installed in 2012; however, since July 2013 these wells have exhibited downward gradients.

2.4.6 Surface Water-Groundwater Interaction

As described in **Section 2.3**, several surface water features are present in the model area. STEP cells all have water elevations above the surrounding water table and these might be sources of recharge to the groundwater system to some degree. Seepage to groundwater from ponds with synthetic double liner systems is assumed to be minimal.

As indicated previously, the Surge Pond likely acts as a flow-through lake. The stage of the Surge Pond is generally slightly below groundwater elevations west of the impoundment and above groundwater elevations east of the lake (**Figure 2-12**). It is therefore assumed that some groundwater enters the impoundment along its west side and seeps from the lake into groundwater on the east side.

East Fork Armells Creek acts as both a source and a sink to the groundwater system. As described in **Section 2.3.1**, this stream has both gaining and losing reaches adjacent to the SOEP and STEP. The reach of the creek between stations AR-1 and AR-9 has been a losing reach for nearly all synoptic events (see **Table 2-3**). The next downstream reach, from AR-9 to AR-8 has also been a losing reach in more than half of the measured events. Below these two reaches the creek gains flow nearly all of the time with only a few exceptions. The two losing reaches lie to the east-southeast of the STEP and may be influenced by pumping associated with the groundwater extraction system as the observed losses have occurred consistently since 2000.

During the April 2014 synoptic gaging event, Hydrometrics (2014) observed groundwater on the east bank of East Fork Armells Creek at station AR-6 flowing toward the creek, but the surface water elevation was slightly higher than groundwater along the west bank. At AR-7, groundwater was flowing towards the creek on the southern west bank, but was slightly lower than surface water just north of there.

During the October 2014 synoptic gaging event, Hydrometrics (2015a) observed that the surface water elevation at site AR-6 was higher than the groundwater elevations measured at the adjacent east and west bank location suggesting that the creek was losing at AR-6 at that time. The groundwater elevation on the southwest bank adjacent to site AR-7 was greater than the stream elevation, suggesting groundwater flow towards the creek; however, the surface water level elevation was slightly higher than the groundwater elevation on the west bank just downstream of AR-7. Groundwater elevations on either side of the creek measured at AR-11 were similar to the surface water elevation, suggesting minimal gain or loss at that location.

2.4.7 Temporal Variation

A number of wells were selected to represent different locations in the SOEP and STEP Area and hydrographs were developed for each. The locations of these wells are shown on **Figure 2-18**, and the hydrographs, organized by location in the SOEP and STEP area, are shown on **Figure 2-19** through **Figure 2-24**. **Appendix E** presents water level data for all the wells regularly monitored within the SOEP and STEP area.

Figure 2-19 shows that groundwater levels in wells north of the SOEP area increased by more than 10 feet between 1985 and 1996. After 1996 water levels began to drop in EAP-205 and 367D, likely in response to pumping at EAP-205. At all other wells monitored levels continued to rise until wells 375D and 376D were converted to capture in wells in 2001. The water level fluctuations from pumping and non-pumping are evident on the hydrographs. Since 2001 water levels in this region have either decreased or remained stable except at well 354D where water levels continue to rise

Figure 2-20 includes hydrographs for wells west of the SOEP. Groundwater levels rose in well EAP-208 between 1979 and1997 in response to filling of the SOEP. After 1997, groundwater levels declined in the wells closest to the SOEP (EAP-208, 371D, and 372D) until about 2008 in response to closure of

370D and 373D all continued to increase until after 369D was converted into a capture well in 2001. EAP-208, was also converted to an extraction well in 2001, as evidenced by the large water level fluctuations illustrating the on and off pumping.

Figure 2-21 presents hydrographs for wells north of the STEP and of pumping well 958D. When pumping began at 958D in 2010, water levels declined in wells with available data from that time (902D and 975D). Subsequently, as pumping in 958D varied, all of the deeper wells to the north responded, with water levels declining following an increase in pumping and rising after pumping decreased. An overall decline in 958D pumping between October 2011 and February 2014 corresponds to an overall rise in water levels in all wells shown on the hydrograph. Hydraulic response in all of these wells (some at notable distance) due to pumping 958D suggests the existence of a continuous zone of elevated permeability that appears to be confined.

Groundwater elevations between the SOEP and the Surge Pond increased between 1979 and 1995 in response to filling of the Surge Pond and SOEP as is evident in the hydrograph for well EAP-119 (**Figure 2-22**). Well EAP-119 was converted to an extraction well in 2001 and pumping was fairly constant until 2007. Most other wells in this area show stable water levels for the period of 1997 to 2015. One exception is well 368D which has a 15 foot decline from 1997 to 2011 and then remains stable. Well 368D is located close to the SOEP and water level declines in that well coincide with termination and of the operation and subsequent drain down of the SOEP in 1997. Nearly all wells in this area show annual fluctuations of 1 to 3 feet, likely associated with operation of the Surge Pond.

Groundwater levels in wells to the southeast of the Old Clearwell (**Figure 2-23**) declined from 1999 to about 2007, after which levels remained relatively stable. All four of the wells show a rise in water levels in late 2007 followed by a return in late 2008 to levels before the rise occurred. This brief rise and fall may be related to the Old Clearwell liner breach and subsequent repair that happened during that time period (see **Section 2.3.4**).

Figure 2-24 includes hydrographs for wells east of the STEP Main Dam. Water levels in two of the wells (EAP-413 and 360A) are relatively stable for the period 1979 to1998. Starting in 1999, wells exhibit a decline in groundwater levels of 4 to 7 feet until about 2009 after which levels remain fairly stable, except in well 982D in which water levels dropped another 3 to 4 feet before stabilizing. All wells in this area have repeated short-term fluctuations, many of which are likely the result of pumping influences from the numerous extraction wells operating in this area. The pattern and magnitude of fluctuations evident for well 981D, for example, are clearly the result of pumping influences.

2.5 WATER QUALITY

Groundwater quality in the SOEP and STEP area has been described by Maxim (2004) and Geomatrix (2007). Recent trends in groundwater quality have been described by Hydrometrics (2016) and NewFields (2014). Dissolved constituents including sulfate, chloride, dissolved boron, magnesium, potassium, selenium, sodium, are present upgradient of the SOEP and STEP area groundwater system. These constituents have also been detected in process pond water from the SOEP and STEP and Plant Site, often at concentrations higher than those that occur in upgradient groundwater (Geomatrix, 2006). Certain samples obtained from wells located downgradient of the SOEP and STEP contained levels of these

these dissolved constituents that are elevated with respect to surrounding groundwater in the area that is not impacted by process water (Maxim, 2004).

Because these constituents are all present in native groundwater, the occurrence of a single constituent in groundwater above baseline levels, described in **Section 2.5.1**, does not necessarily indicate that groundwater has been impacted by process water. A suite of indicator parameters has been historically used to assess whether groundwater has been affected by process ponds (Maxim, 2004; Hydrometrics, 2013). These indicator parameters include Total Dissolved Solids (TDS), specific conductance (SC), dissolved boron, sulfate, and calcium-to-magnesium ratio. Chloride is considered a secondary indicator parameter in this report as discussed in **Section 2.5.1**.

The *Administrative Order on Consent (AOC) Regarding Impacts Related to Wastewater Facilities Comprising the Closed-Loop System at the Colstrip Steam Electric Station (CSES) located in Colstrip, Montana* (MDEQ, 2012) identifies several constituents of interest (COIs) which it defines as those parameters found in soil, groundwater, or surface water that: (1) result from Site operations and the wastewater facilities, and (2) exceed background or unaffected reference area concentrations. COIs include, but are not limited to, sulfate, dissolved boron, selenium, potassium, sodium, magnesium, TDS, and salinity as measured by SC.

2.5.1 Baseline Groundwater Quality

Baseline, or background, groundwater quality for the area near the Plant Site and SOEP and STEP has been characterized by Maxim (2004), Arcadis (2007), and Neptune (2016). Arcadis (2007) calculated baseline screening levels (BSLs) for alluvium, spoils, and bedrock to help evaluate whether concentrations of chemical constituents in groundwater are elevated relative to groundwater not impacted by process ponds in the area.

In 2015, Neptune updated BSLs for evaluating potential groundwater impacts in the Plant Site and SOEP and STEP areas (Neptune, 2016). The preferred BSLs were defined in consultation with the MDEQ as the 95th upper confidence bound on the 90th percentile of the baseline data. This statistic is often termed an upper tolerance limit (UTL), which, in this case can be written as a 95/90 UTL. For the large groundwater dataset, a Random Forests clustering approach was utilized to determine a baseline dataset from which BSLs could be estimated. BSLs were calculated for five different stratigraphic intervals (alluvium, Spoils, Clinker, Coal-Related [Clinker, Rosebud, Interburden, McKay], and Sub-McKay). The updated BSLs for the indicator parameters are summarized in **Table 2-5**.

Table 2-5. Summary of Background Screening Levels (BSLs)

Groundwater Unit	Constituent			
	Dissolved Boron (mg/L)	Chloride (mg/L)	Laboratory Specific Conductance (µmhos/cm)	Sulfate (mg/L)
Alluvium	1.6	45	4270	2600
Spoils	0.818	62	4633	3045
Clinker	4	34	5310	3160
Coal	1.1	20	3550	2061
Sub-McKay	1.3	24	4470	2200

Source: Neptune (2016)

It should be noted that in a few cases, updated BSLs are substantially lower than previous BSLs. For instance, the chloride BSL for alluvium dropped from 213 mg/L to 45 mg/L. The exceedance of a BSL of a single constituent in groundwater is not necessarily an indication of impacts related to process ponds. Neptune (2016) calculated BSLs using data from 197 wells, while Arcadis (2007) used only 15 wells to represent baseline water quality. Arcadis used the 95 percent confidence interval of the 95th percentile (95/95 upper tolerance limit, or UTL) to represent the BSL. Neptune applied the Random Forest method to group groundwater data into baseline and non-baseline samples and then calculated BSLS based on the 95/90 UTL. The BSL calculated by Arcadis (2007) appears to be strongly influenced by a sample from MBMG well P-04 in 2005 which had a chloride concentration of 213 mg/L.

Chloride is considered a secondary indicator parameter in this report because the chloride BSLs appear unrepresentative of site background conditions. This is based on upgradient chloride concentrations and pre-operational chloride concentrations at Units 3 & 4 EHP in groundwater that are higher than the chloride BSLs. In addition, NewFields (2014) indicates that the extent of chloride concentrations greater than the BSL is different from the other indicator parameters in some areas. As such, an exceedance of a chloride BSL alone (when other indicator parameters are below their respective BSLs) is not considered indicative of a process wastewater impact.

2.5.2 Extent of Groundwater Exceeding BSLs

Figure 2-25 through **Figure 2-36** are maps showing the extent of groundwater exceeding BSLs for indicator parameters including dissolved boron, chloride, SC, and sulfate in alluvium, coal related rock, and the Sub-McKay for 2015. **Appendix F** contains the data used to create these figures. The figures were created by contouring concentrations in samples obtained from 52 alluvium wells, 6 coal related rock wells, and 134 Sub-McKay wells. Most of the data (49 wells for alluvium, 4 wells for coal related rock, and 118 wells for Sub-McKay) used to create the maps were taken from groundwater samples obtained during the period March through September 2015. A smaller set of the data used were from samples collected between October and December 2015 (4 wells for alluvium, 2 wells for coal related rock, and 16 wells for Sub-McKay) and one sample collected in 2014 for the Sub-McKay to provide additional spatial coverage.

The shape of the areas of BSL exceedances in places where wells are lacking or minimal is based on the extent of saturated alluvium, which is assumed to exceed BSLs due to seepage from the SOEP. For the Sub-McKay, in areas where data from multiple wells cover a range of depths, the shallowest data point was used because it predominantly represented the highest concentration. The vertical distribution is discussed at the end of this section.

Plume maps depict the horizontal extent of constituents in groundwater exceeding the BSL. Progressive contours illustrate areas of higher concentrations. In some cases the extent of areas of higher concentration is uncertain due to limited data points, and therefore those areas are shown with dashed lines.

Figure 2-25 through **Figure 2-28** show that groundwater in alluvium containing indicator parameters above BSLs for dissolved boron, chloride, SC, and sulfate exhibit a similar pattern. Groundwater above BSLs for these four parameters in the alluvium follows a narrow band from beneath SOEP and extends beneath the middle of the STEP and continues below the dam. Highest concentrations occur beneath SOEP, STEP Cell A and Cell E, and a short distance below the dam.

Figure 2-26 indicates groundwater in all monitoring wells in alluvium along East Fork Armells Creek exceeds the chloride BSL of 45 mg/L. Comparison of this figure to **Figures 2-25**, **Figure 2-27**, and **Figure 2-28** indicates that the extent of groundwater exceeding the chloride BSL in this area is somewhat larger than dissolved boron and substantially larger than for SC and sulfate. Alluvial groundwater exceeding BSLs for SC and sulfate along East Fork Armells Creek occurs in small isolated areas in the vicinity of wells 916A, 935A, and 937A. As was previously noted, the updated BSL for chloride (45 mg/L) is substantially lower than the previous BSL (213 mg/L). Surface water interacts with groundwater within the alluvium along the creek and concentrations of chloride in surface water samples collected from North Flume (AR-1, just upstream from the STEP area) have been ≥ 50 mg/L in all samples collected between 2011 and 2015 (Hydrometrics 2012, 2015c). In addition, there are other known sources for chloride in the area that are not related to process water. For these reasons, the SOEP and STEP may not be the source of chloride concentrations detected above BSLs in several upgradient monitoring wells in East fork Armells Creek alluvium (913A, 918A, 938A, 939A, and 940A). Some of the chloride detected in most alluvial wells in East Fork Armells Creek downgradient of the STEP likely originated from the SOEP or STEP prior to the full buildout of the capture system.

Figure 2-29 through **Figure 2-32** show the extent of groundwater exceeding BSLs for dissolved boron, chloride, SC, and sulfate for wells completed in coal related bedrock. Coal related bedrock in the SOEP and STEP area is limited to locations south of the STEP and southeast of the SOEP (**Figure 2-2**). Water quality data are available for six coal related bedrock wells, located south of the STEP and between the SOEP and Surge Pond.

Groundwater in four of the coal related bedrock wells slightly exceeds the BSL of 1.1 mg/L for dissolved boron (**Figure 2-29**), with the highest dissolved boron concentration being 3 mg/L in 926S. Samples from two wells exceeded the BSL of 20 mg/L for chloride (**Figure 2-30**). Samples from three wells exceeded the BSL of 3,550 µmhos/cm for SC (**Figure 2-31**) and the BSL of 2,061 mg/L for sulfate (**Figure 2-32**). Well 957M, located the closest to the STEP, exhibits exceedances the BSL for all four parameters. Groundwater from wells 926S and 979S, located west of the Surge Pond and southeast of the SOEP, exceeded the BSL for all four and three of the four parameters, respectively. Wells 948M and 121-2 between the STEP and Surge Pond do not have exceedances for any of the four parameters.

Figure 2-33 through **Figure 2-36** show the lateral extent of groundwater exceeding BSLs for dissolved boron, chloride, SC, and sulfate for wells completed in the Sub-McKay. Because these figures include wells covering a range of depths, the depicted spatial distribution of concentrations are integrated vertically (in areas where data from multiple wells cover a range of depths, the shallowest data point was used because it predominantly represented the highest concentration).

Bedrock groundwater that exceeds the BSLs for dissolved boron, chloride, SC, and sulfate show similar spatial patterns. Most shallow bedrock beneath the SOEP and STEP contains dissolved boron, chloride, SC and sulfate at concentrations exceeding BSLs. Groundwater in bedrock units exhibiting concentrations of indicator parameters above the BSLs also extend to the northwest below the STEP Main Dam but do not extend beyond the second line of extraction wells in that area. Areas of highest concentrations of the indicator parameters occur beneath the SOEP and below the dam between the two main lines of extraction wells. However, there are a limited number of Sub-McKay wells beneath the SOEP and STEP to characterize the magnitude of concentrations in bedrock beneath the ponds. Well 951D has lower concentrations of COIs than in alluvial wells beneath the ponds. It is assumed the

higher concentrations of COIs in Sub-McKay wells east of the STEP dam are groundwater that originates primarily in alluvium. Given this uncertainty, dashed lines depict the extent of high concentrations in this area.

A small area of groundwater in alluvium and shallow bedrock south of the SOEP exceeds BSLs for dissolved boron, chloride, SC, and sulfate near well 366S (**Figures 2-25**, **2-26**, **2-27**, and **2-28**). This area of groundwater with elevated BSLs is isolated and does not appear to be related to the SOEP. This area is discussed further below.

To illustrate the vertical distribution of COIs exceeding BSLs, cross-sections shown on **Figure 2-3** through **Figure 2-5** have sulfate concentrations posted at mid-screen points for the wells along with plume contours. The minimum plume contour shown is the sulfate BSL of 2,200 mg/L (for alluvium and bedrock) with successively higher concentration contours of 6,000 and 8,000 mg/L, if present.

Cross-sections through the SOEP (**Figure 2-4**) show that the highest concentrations in that area occur in the fly ash and alluvium underlying the fly ash (wells 967P, 946, and capture well 966A). The sulfate BSL is also exceeded in the SOEP area to the north of the pond in capture wells 375D, 376D, and EAP-205, all in shallow Sub-McKay, and also in the area shallow of Sub-McKay wells 367D and 903D. Concentrations decrease with depth based on downgradient wells 355D, 900D, and 958D.

Cross-section D-D' through the STEP shows sulfate concentrations are highest immediately below the ponds in alluvium wells 921A, 923A, and capture well 924A. Concentrations decrease with depth and are below the BSL in Sub-McKay capture well 958D. Cross-sections A-A' and E-E' indicate that the extent of groundwater east of the STEP exceeding the sulfate BSL does not extend below an elevation of about 3,100 feet amsl.

To further illustrate the three-dimensional distribution of constituents in groundwater at the SOEP and STEP area, three-dimensional plume imagery was developed. **Figure 2-37** presents a three-dimensional plume of sulfate developed using the hand drawn contours and observed sulfate concentrations. The electronic (PDF) version of **Figure 2-37** includes animation showing the extent of the plume at various concentrations and also displays cuts through the plume in north-south slices moving from the eastern end of the plume to the west. The lowest concentration displayed is 2,061 mg/L (the Coal-Related BSL for sulfate). This three-dimensional (3-D) plume was created by interpolation using three-dimensional kriging. In order to provide 3-D data to create **Figure 2-37**, hand drawn isoconcentration contours for sulfate were converted to equally-spaced points using GIS and were then merged with actual sulfate concentration data points from wells. Points generated from the hand-drawn contours were assigned an elevation equal to the middle of the saturated portion of the model layer. Water quality data from wells were assigned x, y, and z coordinates based on the location of the well screen.

2.5.3 Changes in Groundwater Quality

Process water in the SOEP and STEP that has seeped into underlying groundwater has served as sources of indicator parameters to groundwater (Hydrometrics, 2016). A major liner failure occurred following construction of the Cell A liner in 1996 that resulted in scrubber slurry beneath the liner (the liner was subsequently repaired). An accidental liner breach of the Old Clearwell of the STEP in 2007 (see **Section 2.3.4**) likely also contributed to elevated indicator parameter concentrations downgradient of the STEP.

This section discusses changes in groundwater quality at different subareas within the SOEP and STEP over the period from 2005 to 2015. Water quality trends presented and discussed below are based on a qualitative evaluation of plots of water quality data for wells at the site.

2.5.3.1 North and West of SOEP

Figure 2-38 shows trends in groundwater quality for select bedrock wells north and west of the SOEP. This figure indicates that concentrations of indicator parameters in capture wells EAP-205 and EAP-208 and monitoring well 369D exhibit general overall declining trends between 2005 and 2015 (with the exception of an increase in concentrations between 2013 and 2014 in EAP-205). These data suggest that concentrations of indicator parameters in groundwater originating from beneath the north side of the SOEP are decreasing over time.

Concentrations of indicator parameters in wells 376D have varied considerably since 2005. Comparison of concentrations of indicator parameters in this well to pumping rates in well EAP-205 indicate that the concentrations are influenced by pumping rates in EAP 205 and variable pumping at wells 375D and 376D. Pumps at 375D and 376D have periodically been turned off and then on again in response to water quality trends (see pumping rate measurements provided with the Site Report in electronic format). Between 2011 and 2014 average pumping rates in EAP-205 increased from about 0.9 gpm to 2.7 gpm while concentrations of sulfate increased from 2,370 mg/L to 6,930 mg/L, suggesting that EAP-205 may draw in more pond influenced water toward 376D when it is pumping at higher rates.

2.5.3.2 South of SOEP

Figure 2-39 includes charts showing changes in water quality over time for select wells south of the SOEP near the Surge Pond. With the exception of dissolved boron, concentrations of indicator parameters in well 366S and 374S generally increased between 2005 and 2015, particularly chloride, while concentrations in wells 977A generally declined during the same period. Concentrations of dissolved boron in well 926S increased slightly during this period but other indicator parameters in the well remained consistent. Indicator concentrations in well 368D decreased substantially between 2005 and 2008 and then increased between 2011 and 2015. Previous work has suggested that elevated constituent concentrations in this area (NewFields, 2014) may not be related to the SOEP.

2.5.3.3 East of STEP Main Dam

Between 2005 and 2015, several alluvial and bedrock capture wells were installed between the STEP Main Dam and East Fork Armells Creek to improve the efficacy of the groundwater capture system. In addition, well 360A was rehabilitated in 2011 to help improve capture within the alluvial system in the area (Hydrometrics, 2011).

Figure 2-40 includes charts showing changes in indicator parameter concentrations over time for select monitoring wells downgradient of the STEP Main Dam. Concentrations of indicator parameters in alluvial well 360A located just downgradient of the STEP Main Dam Sump have generally increased since 2005, while concentrations in alluvial well 910A at the downgradient end of the STEP Dam alluvial drainage have decreased. Concentrations of indicator parameters have declined in most other alluvial wells in this drainage downgradient of 360A (2015A, 2016A, and 2020A) since they were installed in 2011, although concentrations have increased in 2013A and 2014A since 2011. In addition, concentrations of indicator parameters in several bedrock capture wells including 379D, 906D, 934D,

and 989D exhibit an appreciable decreasing trend between 2008 and 2014. These results suggest that groundwater capture is effectively removing process water-affected groundwater downgradient of the STEP Main Dam.

2.5.3.4 East of D Cell

Figure 2-41 includes charts showing changes in indicator parameter concentrations over time for select monitoring wells east of the STEP Cell D. This figure indicates that concentrations of indicator parameters in alluvial wells in this area 377A, 382A, 994A, 997A, and 998A, all exhibit a decreasing trend since 2009 as a result of groundwater capture in this area.

2.5.3.5 East Fork Armells Creek Alluvium

Figure 2-42 includes charts showing changes in indicator parameter concentrations over time for select monitoring wells in alluvium adjacent to East Fork Armells Creek. This figure indicates that concentrations of indicator parameters in alluvial wells in this area generally exhibit decreasing trends since 2005 as a result of groundwater capture. Concentrations of dissolved boron, SC, and sulfate in wells 918A, 938A, and 939A have all dropped below BSLs.

Chloride concentrations in some alluvial wells completed in East fork Armells Creek alluvium are not decreasing. Considering the BSL for chloride in alluvium was decreased from 213 mg/L to 45 mg/L, groundwater samples from all alluvial wells in East Fork Armells Creek alluvium exceed the BSL in 2015. In addition chloride concentrations in all surface water samples from all East Fork Armells stations upstream of the STEP in 2012, 2013, 2014, and 2015 exceeded 70 mg/L, well above the current BSL. Because of the interaction of groundwater and surface water, much of the source of chloride detected in groundwater water from STEP area wells completed in the alluvium of East Fork Armells Creek is likely from upstream sources and not the SOEP or STEP. In fact, the highest chloride concentrations in surface water have been consistently detected at Station AR-12, which is located upstream of the Plant Site, suggesting that at least a portion of chloride detected in East Fork Armells Creek alluvium wells is from sources upstream of the CSES.

2.5.4 Vertical Movement of Constituents

Examination of groundwater quality data and plume maps for alluvium, coal related rock, and bedrock (**Figure 2-25** through **Figure 2-36**) along with vertical gradient data (**Figure 2-15**) indicate that areas with notable vertical movement of groundwater containing concentrations of indicator parameters above BSLs include the following areas:

- In some years, water infiltrates through the reclaimed SOEP cover and leaches COIs carrying them to underlying alluvium and bedrock. The amount of deep percolation varies annually depending on climatic variables (see **Section 2.6.3.3**);
- Water infiltrating from Cell A, Cell E, and the Old Clearwell, in the STEP area is driving water from alluvium, where present, into underlying bedrock; and
- Constituents in shallow groundwater in a small area west of the Surge Pond, in the area of alluvial wells 366S and 927A and bedrock wells 926S and 979S, are being driven from the alluvium down into underlying bedrock.

2.6 WATER BUDGET

A groundwater budget was developed as part of the conceptual framework that bounds the design of the numerical model. This water budget includes estimated inflows and outflows for various components, along with a range (minimum and maximum) for 12 months leading up to October 2005 and October 2014 (the periods simulated by steady-state numerical modeling) and is summarized in **Table 2-6**. Each component of the water budget was developed as an independent estimate with associated errors thus the water budget does not balance perfectly.

The groundwater budget is represented generally by the following equation:

inflow = outflow + change in storage

Changes in groundwater storage are caused by seasonal changes in groundwater elevations due to rising and lowering of the water table. The water balance presented below assumes a steady-state condition, where inflows equal outflows and there is no change in storage. In reality, transient stresses on the aquifer occur during wet periods, due to changes in pond management and pumping. Transient aquifer stresses are considered as part of the numerical modeling effort.

Table 2-6. Summary of Water Balance for 2004-2005 and 2013-2014

	2004-2005						2013-2014					
	Min (ft^3/d)	Max (ft^3/d)	Estimate (ft^3/d)	Min (gpm)	Max (gpm)	Estimate (gpm)	Min (ft^3/d)	Max (ft^3/d)	Estimate (ft^3/d)	Min (gpm)	Max (gpm)	Estimate (gpm)
Inflows												
Underflow In	1,566	4,039,233	73,362	8	20,982	381	1,566	4,039,233	73,362	8	20,982	381
Surge Pond Seepage	5,103	51,031	16,137	27	265	84	5,103	51,031	16,137	27	265	84
Infiltrating Background Recharge	8,522	14,203	11,362	44	74	59	9,398	15,663	12,531	49	81	65
Infiltrating Clinker Recharge	1,014	7,095	4,054	5	37	21	1,118	7,825	4,471	6	41	23
SOEP Infiltrating Recharge	2,493	4,155	3,324	13	22	17	2,749	4,582	3,666	14	24	19
STEP Pond Seepage	2,127	4,418	3,273	11	23	17	2,135	4,434	3,284	11	23	17
Total IN	20,825	4,120,134	111,512	108	21,402	579	22,069	4,122,768	113,451	115	21,415	589
Outflows												
Underflow Out	664	400,356	57,535	3	2,080	299	664	400,356	57,535	3	2,080	299
Discharge to East Fork Armells Creek	2,588	12,213	7,401	13	63	38	2,588	12,213	7,401	13	63	38
Discharge to Stocker Creek	295	2,951	1,623	2	15	8	295	2,951	1,623	2	15	8
Groundwater Extraction	14,944	29,888	22,416	78	155	116	17,308	34,617	25,963	90	180	135
Total OUT	**18,491**	**445,408**	**88,975**	**96**	**2,314**	**462**	**20,855**	**450,138**	**92,522**	**108**	**2,338**	**481**

Notes: ft^3/d = cubic feet per day; gpm = gallons per minute

The steady-state groundwater balance can be expressed by the following equation, based on significant sources of groundwater recharge and groundwater discharge at the site:

$$GW_{in} + PS + INF = GW_{out} + BF + GE$$

Where:

GW_{in}	=	*groundwater underflow from upgradient of the Study Area*
PS	=	*pond seepage*
INF	=	*infiltrating recharge from precipitation*
GW_{out}	=	*groundwater underflow leaving the Study Area*
BF	=	*groundwater discharge to surface water (baseflow)*
GE	=	*groundwater extraction*

In order to quantify the water balance, a domain must be established. **Figure 2-9** through **Figure 2-14** show the domain in which each component of the water balance is calculated. The domain was established in order to meet requirements of the groundwater flow model (as described below). In general, the model domain margins are designed to run either perpendicular or parallel to groundwater flow. However, because the flow system is variable with depth, there are areas where flow enters the domain obliquely. **Table 2-6** presents ranges of estimated flow rates for each component of the groundwater budget. The following subsections described how the estimates were developed.

The water balance was defined for two time periods: October 2004-September 2005 and October 2013-September 2014. These periods were selected to support the two periods for steady-state model calibration discussed below (**Section 4.0**).

2.6.1 Underflow In

Groundwater entering or leaving an aquifer from or to adjoining areas is referred to as underflow. Underflow into the model domain was calculated using Darcy's Law:

$$Q = KiA$$

Where:

Q	=	*flux*
K	=	*Hydraulic Conductivity*
i	=	*Hydraulic Gradient*
A	=	*Cross Sectional Area*

Each portion of the domain where groundwater is interpreted to cross the domain was assessed. There are four general areas where this occurs:

- From the east towards East Fork Armells Creek in the shallow and mid Sub-McKay;
- From the northwest towards Stocker Creek in the shallow and mid Sub-McKay;
- From the south-southeast beneath East Fork Armells Creek in the shallow and mid Sub-McKay; and
- From the south or southwest in all intervals.

Table 2-7 summarizes the lithologic units that are present at each of the "Underflow In" boundaries. Each of these areas has variable lithology dependent upon the depth. Three depth intervals are presented below for the underflow calculations, including:

- Depth Interval 1- includes the shallow interval that extends from ground surface to the Upper sub-McKay, and basal alluvium (Model Layers 2, 3, 4);
- Depth Interval 2- comprises the depth interval of the middle Sub-McKay (Model Layers 5 and 6); and
- Depth Interval 3 - comprises the deep Sub-McKay and Sub-Robinson down to an elevation of 2,876 feet amsl (Model Layers 7 and 8).

Table 2-7. Primary Lithology and Aquifer Characteristics along Underflow-In Boundary

Location	**Depth Interval 1 Lithology and Hydraulic Conductivity Range/Geometric Mean** (feet/day)	**Depth Interval 2 Lithology and Hydraulic Conductivity Range/Geometric Mean** (feet/day)	**Depth Interval 3 Lithology and Hydraulic Conductivity Range/Geometric Mean** (feet/day)
From East towards East Fork Armells Creek	Alluvium 0.11 to 355/18.3	Mid Sub-McKay 0.03 to 118.4/2.5	NA
From Northwest towards Stocker Creek	Shallow Sub-McKay 0.11 to 242/2.5	Mid Sub-McKay 0.03 to 118.3/2.5	NA
From South-southeast beneath East Fork Armells Creek	Alluvium 0.15 to 355/18.3	Mid Sub-McKay 0.03 to 118.4/2.5	N/A
From South	Shallow Sub-McKay 0.11 to 242/2.5	Mid Sub-McKay 0.03 to 118.4/2.5	Deep Sub-McKay 0.03 to 9/2.5

NA – not applicable no underflow

The saturated thicknesses, gradients, and lengths of these boundaries are also variable depending upon depth. In areas where the flow entering the domain is oblique, the flow was estimated using a series of flow tubes along the boundary. **Table 2-8** summarizes the saturated thicknesses, gradients, and approximate lengths of these boundaries. Lengths of inflow boundaries are measured perpendicular to the direction of groundwater flow inferred from the potentiometric surface maps; these lengths vary with depth.

Based on these estimates, approximately 73,362 feet^3/day (or 381 gpm) are estimated to flow into the domain as "Underflow-In."

Table 2-8. Saturated Thickness, Gradient, and Length along Underflow-In Boundary

	Depth Interval 1			Depth Interval 2			Depth Interval 3		
Location	**Saturated Thickness** (feet)	**Gradient**	**Length Perpendicular to Flow** (feet)	**Saturated Thickness** (feet)	**Gradient**	**Length Perpendicular to Flow** (feet)	**Saturated Thickness** (feet)	**Gradient**	**Length Perpendicular to Flow** (feet)
From East towards East Fork Armells Creek	29	0.02	7330	100	0.008	8280	NA	NA	NA
From Northwest towards Stocker Creek	5	0.007	7843	80	0.005	5690	NA	NA	NA
From South-Southeast beneath East Fork Armells Creek	29	0.011	1150	100	0.01	980	NA	NA	NA
From South	80	0.009	5,200	93	0.008	7,500	160	0.002	8,699

NA – not applicable, no underflow

2.6.2 Pond Seepage

Estimates of potential seepage from lined ponds in the STEP area were calculated by Hydrometrics (2016) and are summarized below. Three of the STEP ponds are single lined ponds (Cell A, Cell E, and the Old Clearwell), and two of the STEP ponds are constructed with double-liner systems (Cells B and D). Separate approaches were used for calculating seepage through the single lined ponds verses the double lined ponds. The methodology assumes the geosynthetic liners are in good condition but have a small amount of "defects" that allow some water to pass through. Calculations are presented in Hydrometrics (2016). **Table 2-9** presents the parameters and estimated seepage rates for the various STEP cells (from Hydrometrics, 2016).

Table 2-9. Pond Seepage Estimates

Cell	**Area** (Acres)[1]	**Head** (feet)	**Qcell** (gpm)
A	25	30	6
E	36	30	9
Old Clearwell	10	30	2
Double Lined Ponds			
	Area (Acres)[1]	**Head** (feet)	Qtotal (gpm)
B, New Clearwell	15.3	30	0.02
D	25	30	0.04

[1] Areas are assumed to be all area within impoundment berm, with the exception of the areas for Cell E and A which are based on the wetted perimeter measured during a survey as reported by Hydrometrics (2016).

Minimum and maximum seepage rates listed in **Table 2-6** assume 35 percent less and 35 percent more than the total 17 gpm.

The seepage through the Surge Pond was estimated using the area of the pond, high and low literature-derived hydraulic conductivity values, and a unit gradient. However, since the Surge Pond is a flow-

through pond, the gradient between the pond and the surrounding groundwater system is not a constant and is much smaller than the head on the pond. Although a unit gradient was assumed for these calculations, in reality, the gradient under the Surge Pond is variable. The high and low hydraulic conductivity values were used to calculate the range of seepage and then the geometric mean of the resulting flux was used as the estimate of seepage.

In this case, the minimum and maximum hydraulic conductivity was based on the low and high-end values for silty clay reported by Driscoll (1991) of 1.32×10^{-3} feet/day and 1.32×10^{-2} feet/day, respectively. The area of the Surge Pond within the domain is 3,875,502 feet^2. Using this value with the geometric mean for hydraulic conductivity resulted in a flux of 16,137 feet^3/day, or 84 gpm (**Table 2-6**). For comparison, Bechtel (1974) estimated seepage from the entire Surge Pond as 112 gpm. Bechtel's estimate, prorated for the area of the Surge Pond within the current model domain, results in an estimate of 65 gpm.

2.6.3 Recharge

This component of the groundwater balance is referring to deep percolation (i.e., infiltrating precipitation minus evapotranspiration), which is somewhat variable in the model area. Measuring actual groundwater recharge is difficult, but it can be estimated through determining soil moisture water balances, analyzing stable isotopes, and, in many cases by balancing the water budget. Rates of recharge were estimated for the following distinct areas:

- Background areas;
- Clinker; and
- SOEP.

Estimates of recharge for these zones are described below.

2.6.3.1 Background

Background areas account for most surface area within the domain (126,300,000 feet^2) of the model. These areas are generally covered in grasses and low shrubs and recharge to the groundwater system within such areas was assumed to be a small percent of annual precipitation. A large portion of precipitation is anticipated to run off to streams or evaporate/transpire before reaching groundwater. Initial estimates of background area recharge rates in previous versions of the model were based on estimates used in a groundwater model developed for Area D of the Rosebud Mine, located west of the CSES (Nicklin Earth and Water, 1999). That model used estimates of background recharge of 0.22 to 0.44 inches/year, which is about 1.5 percent of average annual precipitation. October 2005 and October 2014 background recharge values were calculated to support design and calibration of steady-state models described below (**Sections 3.0** and **4.0**) using the precipitation that fell during the 12 prior months. **Table 2-10** summarizes the precipitation and estimated background recharge for the two time periods evaluated.

Table 2-10. Precipitation and Estimated Background Recharge for 2004-2005 and 2013-2014

Area (feet^2)	Estimated percent of Precipitation	Precipitation Oct 2004-Sep 2005 (inches)	Estimated Recharge Oct 2004-Sep 2005 (feet^3/day)	Precipitation Oct 2013-Sep 2014 (inches)	Estimated Recharge Oct 2013-Sep 2014 (feet^3/day)
171,459,753	1.5%	19.35	11,362	21.34	12,531

2.6.3.2 Clinker Recharge

As described above, clinker outcrops exist around the Surge Pond and elsewhere in the SOEP and STEP area (**Figure 2-2**). Clinker typically has relatively high permeability due to settling or collapse of the rock, which results in secondary porosity. The greater permeability of clinker subsoil relative to other types of subsoil can result in higher rates of recharge.

Literature estimates of recharge through clinker outcrops is not available. Estimates of recharge rates through clinker outcrops were based on previous modeling for the Plant Site area (Geomatrix, 2006 and 2008), where recharge through clinker outcrops (estimated to be an area of 13,110,459 feet^2) was estimated to be approximately 7 percent of annual precipitation. Based on this value, the estimated volume of net recharge in these areas for September 2004 through October 2005 and September 2014 through October 2014 is 4,054 feet^3/day and 4,471 feet^3/day, respectively.

2.6.3.3 SOEP

The SOEP contains fly ash produced by the Units 1 and 2. It is capped by an engineered cover system designed to limit seepage through fly ash in the reclaimed pond. The cover includes soil underlain by porcelanite which in turn is underlain by fly ash. Studies conducted by KC Harvey (2014), Reclamation Research Group, and Hydrometrics indicate that some water percolates through the cover to underlying groundwater.

According to KC Harvey (2014), there is a time delay for water to percolate into the ash under normal precipitation events but an immediate response during heavy precipitation. Drainage through the cap into the ash is highly variable and can be both positive and negative but the cumulative flux stabilizes when averaged over long periods of time (KC Harvey, 2014). KC Harvey (2014) estimated drainage through the cap into the ash between 2011 and 2013 as follows:

2011 - 43 percent of precipitation (10.5 inches)

2012 - Negligible

2013 - 4.6 percent of precipitation (1.24 inches)

Hydrometrics (2016) estimated the drainage rate through the SOEP cap and through the ash to a depth of 20 feet using the computer code HYDRUS. Over a 10-year period (2003 through 2012) the simulated average percolation was 0.569 inches/year or 8.7 percent of average precipitation (Hydrometrics, 2016). The minimum and maximum percolation values were 1.16 and 1.62 inches/year for 2004 and 2011, respectively (Hydrometrics, 2013).

2.6.4 Underflow Out

Underflow out of the model domain into adjoining areas was calculated using Darcy's Law. The only area where groundwater is interpreted to flow out of the model domain is to the north and east as shown on potentiometric surfaces (**Figure 2-9** through **Figure 2-14**).

Lithology along the northeast margin of the model domain varies with depth (see **Section 2.1.3**). **Table 2-11** summarizes the lithologic units and associated range of hydraulic conductivity values that are present at the "Underflow-Out" boundary.

Table 2-11. Primary Lithology and Aquifer Characteristics along Underflow Out Boundaries

Location	Depth Interval 1 Lithology and Hydraulic Conductivity Range/Geometric Mean (feet/day)	Depth Interval 2 Lithology and Hydraulic Conductivity Range/Geometric Mean (feet/day)	Depth Interval 3 Lithology and Hydraulic Conductivity Range/Geometric Mean (feet/day)
North	Alluvium et al. 0.15 to 355/18.3	Middle Sub-McKay 0.03 to 118.4/2.5	Deep Sub-McKay 0.03 to 9/2.5

The saturated thicknesses, gradients, and lengths of the underflow-out boundaries vary with depth. **Table 2-12** summarizes the saturated thicknesses, gradients, and approximate lengths of the boundaries. Based on these estimates approximately 57,535 feet^3/day (299 gpm) are estimated to flow out of the domain as "Underflow Out."

Table 2-12. Saturated Thicknesses, Gradients, and Lengths along Underflow-Out Boundary

	Depth Interval 1			Depth Interval 2			Depth Interval 3		
Location	Saturated Thickness (feet)	Gradient	Length (feet)	Saturated Thickness (feet)	Gradient	Length (feet)	Saturated Thickness (feet)	Gradient	Length (feet)
North	15	0.009	2,780	35	0.008	2,730	190	0.005	20,030

2.6.5 Baseflow

As was discussed in **Section 2.3.1**, East Fork Armells Creek gains flow through much of the reach adjacent to the STEP. The lower reach of Stocker Creek is also assumed to gain flow. Synoptic flow measurements summarized in **Table 2-3** were used to calculate minimum and maximum gaining rates for the creek within the domain. Streamflow has not been measured downstream of station AR-10 and so gain and loss estimates are not available for the northern-most reach of the creek within the domain.

To help estimate streamflow gains within the domain, East Fork Armells Creek flow rates were first estimated for upstream and downstream ends of the domain. The upstream flows were estimated assuming linear interpolation between station AR-2 and station AR-1 (**Figure 2-1**). The model domain crosses East Fork Armells Creek at approximately 9,520 feet downstream of AR-12, and interpolated flows at that point range from 290 to 1,000 gpm.

Flows at the downstream end of East Fork Armells Creek were estimated assuming the gain per unit length for the reach downstream of AR-10 is similar to the average gain per unit length between AR-6 and AR-10 (**Figure 2-8**). The gain in flow per unit length between AR-6 and AR-10 was calculated for each synoptic run and averaged (May 21, 2003 rates were not used due to an anomalously high measurement at AR-10). The average gain in flow per unit stream length between AR-6 and AR-10 is 0.015 gpm per foot. This rate was multiplied by the 7,400 feet of stream between AR-10 and northern end of the model domain yielding an estimated gain of 113 gpm for that reach. The 113 gpm was then added to minimum and maximum estimated flows at AR-10, yielding a range of estimated flows at the downstream boundary of 305 to 1,183 gpm. Subtracting estimated flows at upstream boundary from the downstream boundary (15 to 183 gpm) yields a range of streamflow gain within the model domain of 2,588 to 12,213 feet^3/day (13 to 63 gpm) with an average value of 7,401 feet^3/day (38 gpm).

Flow in the lower 100 to 1,000 feet of Stocker Creek appears to be sustained by groundwater during most times of the year based on aerial photography. Because flow measurements are not available for Stocker Creek, it was assumed that the creek may gain flow at a similar rate per unit length as the lower reach of East Fork Armells Creek. Based on this assumption, Stocker Creek is estimated to gain 295 to 2,951 feet^3/day (2 to 15 gpm) of flow from groundwater with an average value of 1,623 feet^3/day (8 gpm).

2.6.6 Groundwater Extraction

Talen has installed an extensive groundwater capture system that consists of capture wells and drains within the SOEP and STEP area (**Figure 2-43**). Between late 2005 and 2014, several of the wells shown on **Figure 2-43** were either converted from monitoring wells into capture wells or were installed for the purpose of groundwater capture. The majority of the groundwater capture wells are located east of the STEP main dam and are completed in shallow bedrock or alluvium (shown on cross-section A-A' on **Figure 2-3** and E-E' on **Figure 2-5**).

Groundwater capture wells are routinely monitored for flow, hours operated, water level, and specific conductance. However, the extraction systems construction prohibit the installation of individual flow meters, and the pumping rates are measured at each well head through a sampling port with no other wells in a given extraction system pumping. As a result, the flow is measured without the back pressure that is present on the system under normal operating conditions. Less water is pumped when the system is back pressured, resulting in an overestimate of measured flow and calculated capture volumes. In some cases the overestimate can be 100 percent or more (Hydrometrics, 2013), though recent evaluations (Hydrometrics, 2015b) suggest that actual current pumping rates for capture wells are about 25 percent lower than measured rates. Pumping rate measurements are provided separately in electronic format (with the Site Report).

Table 2-13 presents the estimated pumping rates for each well that was actively pumped during October 2005 and/or October 2014. These pumping rates are 75 percent of the measured rates for July, August, and September of 2005 and 2014 with a few exceptions. Pumping rates in multiple wells in two different areas below the STEP Main Dam were reported to have increased significantly around January 2012. These wells include 987D, 906D, 984D, 905D, 911D, 380D, 968D, 960D, and 961D. Analysis of pumping records showed pumping rates increased in these wells with no change in pumping water level. Discussions with Hydrometrics indicated a potential change in measurement methods was likely the reason for the discrepancies and historic pumping rates were more likely representative of

current pumping rates. To estimate a likely pumping rate, an average pumping rate for each well was estimated using rates collected from January 2009 through December 2011, a relatively stable pumping period.

Additional adjustments were made to simulated pumping rates for the steady-state model for wells 2024D, 991A, 993D, and 994A. Well 2024D was set to 75 percent of the average monthly pumping rate for September 2014 as the well was not pumping in July and August 2014. Well 991A, 993D, and 994A pumping rates were both set at 0 gpm as these wells were not pumped in September 2014 and only intermittently pumped in October 2014.

Table 2-13. Summary of Estimated Groundwater Extraction Rates: 2005 and 2014

Well	October 2005 Estimated Pumping Rate (gpm)	October 2014 Estimated Pumping Rate (gpm)	Well	October 2005 Estimated Pumping Rate (gpm)	October 2014 Estimated Pumping Rate (gpm)
2000D	-----	7.49	934D	2.99	0.45
2003D	-----	6.22	938A	20.26	-----
2008D	-----	2.51	940A	6.18	-----
2013A	-----	16.25	943A	2.37	6.73
2016A	-----	1.87	944A	10.48	-----
2019D	-----	3.74	945A	2.91	8.12
2021D	-----	1.13	958D	-----	0.97
2024D	-----	2.23[b]	960D	-----	2.46[a]
369D	0.32	0.0003	961D	-----	1.32[a]
375D	0.53	2.24	962D	-----	5.08
376D	0.21	0.001	963D	-----	4.97
377A	8.26	0.16	966A	-----	4.47
378A	3.98	0.34	968D	-----	0.94[a]
379A	1.24	0.04	969D	-----	0.01
380D	1.01	1.03[a]	970D	-----	0.08
382A	0.001	2.79	976D	-----	0.75
383D	0.98	0.41	984D	-----	1.14[a]
393D	3.51	0.40	985A	-----	0.09
905D	-----	1.69[a]	987D	-----	1.85[a]
906D	-----	2.29[a]	988D	-----	1.57
910A	4.24	0.0005	989D	-----	1.43
911D	0.90	1.13[a]	991A	-----	0[c]
913A	9.44	0.002	993D	-----	0[c]
916A	14.01	13.61	994A	-----	0[c]
922A	-----	4.57	997A	-----	1.09
924A	0.14	0.03	998A	-----	2.40
927D	0.56	2.24	EAP-119	0.13	0.32
928D	4.19	5.03	EAP-205	0.43	0.96
932D	8.24	3.47	EAP-208	0.50	0.48
933D	0.52	0.12	PW-704D2	-----	9.97

Notes: a 75% of rates from January 2009 through December 2011
b Well 2024D set to 75% of the average pumping rate for September 2014
c Wells 991A, 993D, and 994D pumping rates set to 0 gpm

Total estimated groundwater extraction from 28 wells and the STEP Main Dam toe drain in October 2005 was 116 gpm, and the total estimated groundwater extraction from 54 wells and the toe drain in October 2014 was 135 gpm. The maximum rates for the two periods was estimated to be 155 gpm for 2005 and 180 gpm for 2014, which is the total of the unadjusted measured extraction rates. Minimum estimated extraction rates are 78 gpm for 2005 and 90 gpm for 2014, assuming actual pumping rates are 50 percent of measured rates.

2.7 Changes to Conceptual Model Since 2007

Geomatrix (2007 and 2008) provided a detailed description of the conceptual model of groundwater flow and solute transport near the SOEP and STEP and Plant Site areas. NewFields (2014) provided an update to the numerical model incorporating data through 2010, but did not include a detailed update of conceptual model.

Additional hydrogeologic data have been collected since the SOEP and STEP conceptual model was last updated. These data include information from wells installed in the SOEP and STEP area up to 2010 (NewFields, 2014) and from wells installed from 2010 to the present (listed in **Table 2-14**).

Table 2-14. Wells Installed 2010-2014

Well ID	Aquifer	Install Date	Total Depth*	Well ID	Aquifer	Install Date	Total Depth*
360A	Alluvium	8/31/2011	25**	2011D	Sub-McKay	12/15/2010	152
985A	Alluvium	4/7/2012	32	2012D	Sub-McKay	12/15/2010	60
2013A	Alluvium	8/31/2011	26	2018D	Sub-McKay	8/31/2011	100
2014A	Alluvium	8/31/2011	21	2019D	Sub-McKay	11/16/2011	71
2015A	Alluvium	8/31/2011	24	2021D	Sub-McKay	4/10/2013	49
2016A	Alluvium	5/11/2012	44	2022D	Sub-McKay	8/20/2012	80
2017A	Alluvium	8/31/2011	29	2023D	Sub-McKay	8/20/2012	83
2020A	Alluvium	11/16/2011	26	2024D	Sub-McKay	7/17/2013	155
2028A	Alluvium	10/15/2012	35	2025D	Sub-McKay	8/20/2012	105
2035A	Alluvium	4/7/2014	43	2026D	Sub-McKay	8/20/2012	142
2038A	Alluvium	4/8/2014	47	2027D	Sub-McKay	10/15/2012	48
952D	Sub-McKay	8/31/2011	100	2029D	Sub-McKay	10/15/2012	57
953D	Sub-McKay	7/17/2013	140	2030D	Sub-McKay	10/16/2012	44
2003D	Sub-McKay	4/7/2010	40	2031D	Sub-McKay	6/10/2013	45
2004D	Sub-McKay	4/16/2010	45	2032D	Sub-McKay	6/10/2013	134
2005D	Sub-McKay	4/16/2010	66	2033D	Sub-McKay	6/18/2013	160
2006D	Sub-McKay	4/16/2010	38	2034D	Sub-McKay	4/7/2014	78
2007D	Sub-McKay	4/16/2010	130	2036D	Sub-McKay	4/7/2014	90
2008D	Sub-McKay	12/15/2010	42	2037D	Sub-McKay	4/8/2014	80
2009D	Sub-McKay	12/15/2010	152	PW-704D1	Sub-McKay	12/4/2012	130
2010D	Sub-McKay	12/15/2010	154	PW-704D2	Sub-McKay	12/4/2012	80

*Total Depth: Depth to bottom of screen, in feet

** 360A previously existed but was redrilled and completed in 2011

The following new information was considered in the modeling refinement discussed in this report:

- Capture wells are pumping at approximately 75 percent of the measured extraction rates;
- Lithologic, water level, and water quality, for wells 2019D through 2038A; this includes wells installed south of the SOEP, in alluvium beneath the SOEP, north, east, and south of the STEP Main Dam;
- Water level data obtained from all wells between 2007 and December 2015;
- Water quality data obtained between 2007 and December 2015;
- Aquifer test data (37 pumping and slug tests) from numerous wells between October 2007 and May 2014 at wells 2003D through 2038A;
- Synoptic gaging data collected on East Fork Armells Creek between 2007 and March 2015;
- Regional Montana Bureau of Mines and Geology Groundwater Information Center (GWIC, 2016) groundwater level data for establishing elevations at model edge boundaries; and,
- Water level data from the Rosebud Mine observation well network (Western Energy Company, 2013 a, b, c, d, and e).

The following is a summary of refinements to the conceptual model since 2007:

- Pumping data in the central area of the model indicate that there is hydraulic connection between wells 399D, 2009D, 2010D, 2011D, 975D, 902D, and 958D. In addition to refinement of layer elevations using data from new wells, the Sub-McKay is now conceptualized as a continuous sandstone in this area overlain by a confining unit;
- Changes in water management in the STEP area have occurred since 2007. Updates include: installation of a passive evaporation system north of Cell A (which was removed in 2015), installation of Cell B and conversion to the New Clearwell; installation and operation of Cell D; and construction of the Paste Plant and pasting in Cell E reducing assumed seepage. Accounting for these changes has resulted in the revised amount and spatial distribution of calculated seepage in the STEP area;
- Estimates of recharge through Clinker outcrops have increased;
- Capture well pumping rates are assumed to be approximately 75 percent of the measured rates; and
- Groundwater flow in the deep Sub-McKay/Sub-Robinson is to the northeast (rather than north).

2.8 Conceptual Groundwater Model Summary

The hydrostratigraphy in the SOEP and STEP area is complex. Part of the stratigraphic sequence has been eroded away along East Fork Armells Creek. Alluvium within the floodplain consists of fine-grained overbank deposits overlying coarser channel deposits consisting of sand and gravel.

Figure 2-44 is an animated block model (paper copies of this report contain a static image) illustrating the conceptual understanding of the hydrogeologic system in the SOEP and STEP area. The block model, in combination with the estimated water balance shown in **Table 2-6**, describe the current

understanding of surface water-groundwater interaction and groundwater flow, and how this relates to the spatial distribution of contaminants.

Groundwater flow in shallow bedrock and alluvium generally flows northeast under the SOEP and STEP and then turns northwest parallel to East Fork Armells Creek. Groundwater flow in the deep Sub-McKay follows a more regional pattern that is generally from southwest to northeast beneath the SOEP and STEP area. Vertical hydraulic gradients in all well pairs evaluated are downward from alluvium to the shallow Sub-McKay and into capture wells or the underlying deep Sub-McKay.

Underflow is the major source of water entering the groundwater system in the SOEP and STEP area making up about 65 percent of the inflow. Areal recharge (background and clinker) and infiltration through the SOEP account for 15 percent and 3 percent, respectively, of water entering the groundwater system. Seepage from the surge pond provides an estimated 14 percent of the groundwater inflow. Seepage from single lined STEP cells (A, E, and Old Clearwell) accounts for the remaining 3 percent of inflow to the groundwater system.

Underflow out is about 62 percent of system outflow. Groundwater capture via drains and wells is another major source of outflow for the groundwater budget, estimated to be about 28 percent of water leaving the groundwater system. Some shallow groundwater enters alluvium adjacent to East Fork Armells Creek and Stocker Creek and accounts for and estimated 8 percent and 2 percent, respectively of water leaving the groundwater system.

Most groundwater with concentrations of constituents above BSLs is currently being intercepted by the groundwater capture system and returned to lined ponds. Some of this groundwater is also being captured by the toe drain at the base of the STEP Main Dam. The capture system depresses the water table and collects both impacted and non-impacted groundwater. The current capture system is preventing east-flowing groundwater from the SOEP and STEP areas from entering East Fork Armells Creek alluvium. Groundwater that is not captured by pumping in the vicinity of the SOEP generally flows very slowly to the northeast.

Process pond water contains dissolved constituents that are also present in upgradient groundwater that is un-impacted by sources within the SOEP and STEP area, making it difficult to draw distinct lines between impacted and un-impacted groundwater. Groundwater quality that is influenced by current and former process ponds at the SOEP and STEP area is characterized by levels of parameters such as dissolved boron, chloride, SC, and TDS that are elevated as compared groundwater in areas not affected by process ponds.

Currently, groundwater is not used for domestic or livestock purposes in the SOEP and STEP area. One exception is well 901D that in 2015 was equipped with a pump for seasonal stock water use.

3.0 NUMERICAL GROUNDWATER MODEL

The SOEP and STEP numerical model described in this report (referred to as the "current" SOEP and STEP model) is designed to serve as a tool to assess the effectiveness of the groundwater capture well system installed by PPLM at the SOEP and STEP as well as provide a better understanding of the interactions between evaporation ponds and surge ponds, groundwater, and surface water in the vicinity. The current SOEP and STEP model includes refinements to the previous model developed by NewFields (2014). The primary refinements include adjustments to model boundaries, layer elevations, grid discretization, and assignment of model properties based on data collected through October 2014. The model geometry and discretization were refined to more accurately simulate groundwater flow in distinct stratigraphic intervals. The conceptual model described in **Section 2.0,** above, provides the foundation for the refinements made in the development and parameterization of the current SOEP and STEP model.

NewFields used hydrologic data sets to specify boundary conditions for several time periods for the site. The simulated time periods for the current model are:

- 2005 Steady-State (October) – represents conditions prior to capture system pumping;
- November 2005 through December 2007 Transient – incorporates a period when large changes in transient aquifer stresses occurred including the initiation of capture system pumping and a breach in the Old Clearwell liner;
- 2014 Steady-State (October) – includes the most recent comprehensive data set available; and
- Pumping Tests: 958D and 966A.

The first three time periods are simulated with three separate models of identical construction but with different pumping and recharge specifications that represent the time period simulated. Variations of the model were also used to simulate the listed pumping tests to assist in calibration of the main model.

Following calibration, the model was used to assess the effectiveness of capture systems. The model code, design, and calibration of the SOEP and STEP model are discussed below.

3.1 CODE SELECTION

The current SOEP and STEP model was developed using the U.S. Geological Survey (USGS) code MODFLOW-SURFACT Version 3 (HydroGeologic, 1998). MODFLOW-SURFACT was used because it allows for variable saturation. The USGS code MODPATH Version 3 (Pollock, 1994) was used to assess capture by simulation of advective transport of constituents in groundwater. The graphical-user-interface software Groundwater Vistas© (Version 6.75, Build 8) was used for model pre- and post-processing.

3.2 MODEL DOMAIN

The model domain was expanded from the previous SOEP and STEP model to move external model boundaries farther from the area of interest and capture wells. Expansion of the domain was also prompted by review of potentiometric surfaces for the deepest portion of the model. The previous

model had no-flow boundaries parallel to both East Fork Armells Creek and Stocker Creek for all model layers which directed flow parallel to these boundaries. Review of expanded potentiometric surface maps for the deep Sub-McKay system suggests that deeper regional flow is more northeasterly and crosses under East Fork Armells Creek (**Figure 2-14**).

The current model domain extends east to include alluvial sediments and low hills east of East Fork Armells Creek and north to include the alluvial sediments and low hills northwest of Stocker Creek, where the previous model did not. The model domain also extends south to an identified groundwater divide at the Surge Pond and south and west to approximately 1,500 feet upgradient of the reclaimed Stage I Pond (**Figure 2-12**).

The revised model domain was developed after producing a series of depth specific potentiometric surfaces which incorporated regional data. The shape of the model domain was developed in an attempt to have model boundaries generally parallel or perpendicular to groundwater flow. As a result, the active model domain in Shallow (Layers 2, 3, and 4), Intermediate (Layers 5 and 6), and Deep (Layers 7 and 8) are different (**Figure 3-1**). The domain for the revised model was expanded to the northwest, northeast and east.

The expanded domain for the revised model encompasses about 4,420 acres and extends approximately 16,500 feet in the east-west direction and 14,000 feet in the north-south direction. The revised model domain was discretized (**Figure 3-2**) into 189 rows and 268 columns with 312,032 total active cells. The model grid is rotated 58 degrees to the east and telescopes from 25-foot column and row spacing in the primary areas of interest in the central part of the model domain to a maximum 100-foot row and 300-foot column spacing in the outer portions of the model domain. The finer grid-spacing provides greater horizontal discretization of the hydrologic properties and boundary conditions (including capture wells), which provides better resolution for the simulation of groundwater flow within the areas of greatest interest.

3.3 MODEL LAYERS

The revised model domain was subdivided into eight layers, the same as the previous (NewFields, 2014) version. However, layer elevations were updated from the previous model version using data from wells installed since 2010. Model layers are summarized (top to bottom) as follows:

- Layer-1 – Land surface for STEP confining conditions and to simulate Surge Pond (see below).
- Layer-2 – Fly ash (SOEP), shallow Alluvium, shallow Colluvium.
- Layer-3 – Middle Alluvium. Also includes lower Interburden and McKay Coal, where present.
- Layer-4 – Deeper Alluvium, Upper Sub-McKay.
- Layer 5 – Mid-Level Sub-McKay, elevations 3,077 to 3,227 feet amsl.
- Layer 6 – Mid-Level Sub-McKay, elevations 3,057 to 3,183 feet amsl.
- Layer 7 – Deep Sub-McKay and Sub-Robinson, elevations 2,976 to 3,117 feet amsl.
- Layer 8 – Deep Sub-McKay and Sub-Robinson, elevations 2,875 to 3,051 feet amsl.

The land surface elevation utilized in the model was developed from Shuttle Radar Topography Mission (SRTM) digital elevation 1-arc-second resolution (approximately 100-feet by 100-feet resolution) data

(Rodriguez, 2005) merged with original land surface elevation contours derived from USGS 7.5-Minute quadrangle maps beneath the STEP and the Surge Pond.

Layer bottom elevations were primarily established as the contact between different strata including fine and coarse grained alluvium, major coal, sandstone, and siltstone strata as described in **Section 2.1.2** and presented on **Figure 2-2**. Major continuous coal, sandstone, and siltstone strata are typically represented within a single layer. However, these major strata are not typically laterally or vertically continuous and entire layers do not represent distinct aquifer (high permeable) or confining (low permeable) units. The layer bottom elevations were also further divided based on arbitrary depths to provide greater resolution for groundwater elevations and flow and to better match the screened intervals of monitoring and capture wells.

The layer elevations extend from ground surface (top of Layer 1), at a maximum of 3,303 feet amsl, to the bottom of Layer 8 at an elevation of 2,875 feet amsl. A list of wells referenced in **Section 2** and used in the numerical model are provided in **Appendix G** along with the associated model layer or layers.

A model cross section through the STEP area is shown on **Figure 3-3**, and two of the cross sections presented in **Section 2.0** are repeated on **Figure 3-4** showing the model layers and associated units. Alluvium was split between three model layers (Layers 2, 3, and 4) to accommodate bedrock layers pinching out due to erosion and to simulate alluvium beneath the Stage I Pond. Layer 2 of the model simulates flow in the fly ash of the Stage I Pond, upper interburden in the western portion of the model domain, and colluvium/alluvium near the land surface. Model Layer 3 represents the lower interburden in the western portion of the model domain, the McKay Coal in the vicinity of wells 948M and 957M, and middle alluvium. Model Layer 4 represents the upper Sub-McKay bedrock and basal alluvium. Layers 5 through 8 of the model represent the middle Sub-McKay bedrock through the Sub-Robinson bedrock.

Model layer elevations were adjusted in several portions of the model based on lithologic contacts from well logs for new wells installed since 2010 (wells 2018D through 2038A). Adjustments were made such that layer transitions corresponded with lithologic contacts, such as: 1) contacts between notable layers of sandstone with shale/siltstone; 2) contacts between fine and coarse grained alluvium; and 3) at the base of alluvium. The lithologic contact elevations at wells 2022D, 2023D, 2031D, 2025D, 2037D and 2038A required local adjustment of the bottom of Layer 3 (top of Layer 4). Similarly lithologic contact elevations at wells 2020A, 2022D, 2023D, 2024D, 2025D, 2026D, 2027D, 2028A, 2029D, 2030D, 2034D, 2035A, 2036D, 2037A, and 2038A required local adjustment of the bottom of Layer 4 (top of Layer 5).

In addition to changes based on new well log information, layer elevations were also adjusted in the central portion of the model (near wells 399D, 2009D, 2010D, 2011D, 975D, 902D, and 958D) to better represent the degree of hydraulic communication between wells observed during pumping at well 958D as described in **Section 2.4.7.** Initial simulations of pumping in well 958D did not result in a hydraulic response in these surrounding monitoring wells. Lithologic information from these wells indicate they all communicate within a thick sandstone layer that is capped with a fine-grained bedrock layer. To help simulate hydraulic communication between well 958D and surrounding monitoring wells within the sandstone layer, the top elevations of Layers 5 and 6 and a small area of the bottom of Layer

4 were adjusted. As a result of the layer elevation adjustments target wells 399D, 2009D, 2010D, 2011D, 975D, and 902D were moved from Layer 5 to Layer 6, which now represents the sandstone layer.

For the variably saturated option in MODFLOW-SURFACT layer types must be defined as either Type 3 or Type 0. Model Layers 1 through 4 are simulated as Type 3 layers (convertible layers), which allow transmissivity to vary dependent on saturated thickness and simulate groundwater flow under either confined or unconfined conditions. Layers 5 through 8 are simulated as type 0 (confined) layers.

3.4 BOUNDARY CONDITIONS

The groundwater flow system was established by assigning model boundaries to the model domain. Model boundaries coincide with natural hydrologic boundaries that include groundwater flow into and out of the active model domain, areas where groundwater flow is restricted, and areas of parallel groundwater flow. The boundaries established for the current model represent the many stresses affecting the aquifer that create a complex flow field. Assigned boundary conditions are illustrated on **Figure 3-5** (Layer 1 and 2), **Figure 3-6** (Layer 3 and 4), and **Figure 3-7** (Layer 5 and 6, and Layer 7 and 8) and are described below.

3.4.1 General Head Boundaries

The General Head Boundary (GHB) Package was used to represent the groundwater underflow into and out of the active model domain. A GHB is a head-dependent boundary where the flow into or out of the model is equal to the difference between the head in the model cell and the head at a distance from the model boundary times the estimated conductance of the GHB. The conductance is estimated by the following equation:

$$Conductance = WTK/L$$

Where: W = *Width of cell*
T = *Saturated thickness of cell*
K = *Hydraulic conductivity*
L = *Distance to the assigned head value*

GHB cells were assigned to match observed and inferred underflow into and out of the model domains as depicted on the potentiometric surface maps (**Figure 2-9** through **Figure 2-14**). The assigned GHB parameters are provided in **Appendix H**. The boundaries were established far enough from the SOEP and STEP area to minimize potential boundary influences on the model results.

The width, saturated thickness, and hydraulic conductivity of each GHB cell were populated by Groundwater Vistas based on actual width, saturated thickness, and hydraulic conductivity assigned to that cell.

Heads were assigned to GHB cells in the 2014 steady-state model based on potentiometric surface maps. Potentiometric surfaces described in **Section 2.4.1** were used to assign the boundary head values and estimate distances to the lines of equal head potential. The 2014 shallow potentiometric surface map (**Figure 2-12**) was used to assign heads to the GHB cells in Layers 2, 3, and 4. GHBs representing Layers 2, 3, and 4 are shown on **Figure 3-5** and **Figure 3-6**.

Head values and distances to the boundary for GHBs cells in Layers 5 and 6 were assigned based on the 2014 Mid Sub-McKay potentiometric surface map (**Figure 2-13**). A downward gradient between Layers 5 and Layer 6 GHB's was induced based on an average estimated downward gradient of 0.37. Initially, most heads specified in GHB cells in Layer 6 (with the exception of the downgradient East Fork Armells Creek boundary reach 25 and 26) were set 20 feet below the elevation of the Layer 5 GHB elevations based on estimated downward gradients. The elevation was adjusted during calibration and resulted in heads in Layer 6 set 10 feet below the heads in Layer 5, with the exception of the heads in the upgradient southwest GHB which are set at 8 feet below the heads in Layer 5.

GHB cells in Layers 7 and 8 were parameterized based on potentiometric surfaces. The potentiometric surface established in the model domain for Layer 7 is provided as **Figure 2-14**. The potentiometric surface established for Layer 8 was based on sparse data and not provided in this report.

The GHBs for the 2005 steady-state and 2005-2007 transient models were established using the 2014 general head boundaries. Available data outside the model domain are sparse, and therefore the 2014 potentiometric surfaces outside and near the edges of the active model domain were also used for the 2005 steady-state and 2005-2007 transient models.

3.4.2 No-Flow Boundaries

No-flow boundaries were assigned along the perimeter of the active model domain where groundwater flow direction was assumed to be parallel to the model boundaries. The no-flow boundaries in the 2014 steady-state model were established from the respective potentiometric surface maps discussed in **Section 2.4.1**, above.

3.4.3 River Package Boundaries

The River Package was used to simulate groundwater and surface water exchanges along East Fork Armells Creek, the lower reach of Stocker Creek that is considered perennial, and between the Surge Pond and the groundwater flow system (**Figure 3-5**). River cells for the three areas were assigned unique reach numbers, and the East Fork Armells Creek was further divided into multiple reaches based on the location of stream gages. The different reaches facilitate quantifying model-predicted fluxes, and establishing surface water elevations from field measurements.

The River Package is a head-dependent boundary condition that allows water to move into and out of the model cell based on the difference between the groundwater elevation and stream stage. A conductance term assigned to the river cell restricts the flow rate exchange. The conductance is estimated by the following equation:

$$Conductance = KLW/D$$

Where:

K	=	*Hydraulic conductivity*
L	=	*Length of cell*
W	=	*Width of cell*
D	=	*Riverbed Thickness*

Parameter specifications for the surface water bodies are included in **Appendix I**, and discussed below.

3.4.3.1 East Fork Armells Creek

Stream elevations from synoptic flows measured at gaging stations along East Fork Armells Creek (see **Figure 2-1**) were used to assign stage elevations within the model. River Package cells were assigned elevations by dividing the length of East Fork Armells Creek in the model domain into eight reaches, coincident with the location of the gaging stations. River Package elevations were assigned at the gaging locations based on surveyed elevations and extrapolated between the reaches. The gaging stations were used to divide East Fork Armells Creek into the following reaches:

- Reach 0 - southwest model boundary to gaging station AR-1 (also known as the North Flume);
- Reach 1 - from station AR-1 to AR-9;
- Reach 2 - from station AR-9 to AR-8;
- Reach 3 - from station AR-8 to AR-7;
- Reach 4 – from station AR-7 to AR-6;
- Reach 5 – from station AR-6 to AR-11;
- Reach 6 – from station AR-11 to AR-10; and,
- Reach 7 -from station AR-10 to the northern model boundary.

River stage values measured in 2014 were not used in the model. In 2014 stage was measured at all of the gages only in May, but those were collected during an unusually high spring runoff, while the model simulates a period of seasonally low water conditions. Instead, River Package cells were assigned stage values based on data collected during the May 2012 synoptic gaging event which includes the most complete and recent synoptic measurements completed during a relatively low water condition.

River cell elevations were specified by extrapolating a slope between measured gage elevations for Reaches 1-6. For Reach 0 and 7 the slope was specified between the measured elevation at the gage in that reach and an elevation from the USGS topographic map at the model domain edge.

Stream stage values were extrapolated between AR-1 and AR-7 for Reach 1 (AR-1 to AR-9), Reach 2 (AR-9 to AR-8), and Reach 3 (AR-8 to AR-7), because elevations were not determined at stations AR-9 and AR-8 during the 2012 synoptic event. River stage values for Reach 1 were further adjusted during calibration by flattening the gradient along the upstream portion of this reach to decrease flow out of and increase flow into the model along this reach.

Assigned 2012 stage values for River Package cells were then adjusted to approximate October 2014 levels. The only reliable stage measurement available for October 2014 was from Station AR-1 (North flume). The most complete round of stage elevations at surface water stations within the model domain (AR-1, BPE, BPW, CHE, AR-6, AR-7, and AR-11), for conditions similar to October 2014 were measured May 2012. To help establish stage elevation for these stations representative of October 2014 conditions, May 2012 stage data at these staff gages were adjusted by subtracting the difference between the measured elevation at AR-1 (North Flume) in May 2012 (3,185.36, feet, amsl) and October 2014 (3,185.12 feet, amsl). Stage elevations for River Package cells corresponding to these stations were assigned these adjusted values, and stage values for River Package cells between surface water stations were assigned by interpolating stage between adjacent stations.

River stage values assigned to the 2014 steady-state model range from 3,192.49 to 3,121.45 feet amsl. River Package cells in the 2005 steady-state model were assigned the same elevations as in the 2014 steady-state model. The 2005 and 2014 models use the same stage values because river elevations in October 2014 and October 2005 are assumed to be comparable based on comparison of hydrographs of wells completed in alluvium near East Fork Armells Creek.

River Package cells in the transient model were assigned variable monthly stage elevations based on field measurements, where available. Where monthly stage data were not available, stage was estimated based on seasonal changes in water levels measured in well 918A, which is completed in alluvium adjacent to the East Fork Armells Creek. The measured water levels in 918A were interpolated using a cubic spline algorithm to provide daily estimates of water levels that were then averaged over each stress period. The monthly change in estimated water levels in well 918A was then applied to stage values from the steady-state models.

Stream length was assigned based on the length of the stream extending through the cell. The width of the stream in each river cell was assigned a value of 10 feet which was estimated using aerial imagery. Site-specific data are not available for stream bed thickness and hydraulic conductivity. These parameters were assigned initial values of 1 foot and 25 feet/day, respectively, based on observations of stream bed material and a representative hydraulic conductivity value for fine to medium sand.

3.4.3.2 Stocker Creek

Stocker Creek lies in the extreme northwest portion of the model domain. Based on available aerial photographs, the upper reaches of the creek appear to flow intermittently, while the lower 1,000 or so feet appears to flow most times of most years. Only the presumed perennial portion of the creek was represented in the model with River Package cells.

River Package cell elevations for the 2005 and 2014 steady-state models were specified by extrapolating a slope between assigned stage elevations at the confluence with East Fork Armells Creek and the groundwater elevation measured in October 2014 in Alluvial well 357A. Well 357A is completed adjacent to the creek at the furthest upstream point the creek is represented in the model. Monthly stress period stage values for the transient model were assigned by applying the measured change in water level for well 357A to Stocker Creek stage values from the steady-state models.

The simulated stream length parameter for each cell was assigned based on the length of the stream extending through the cell. The width of the stream in each river cell was assigned a value of 3 feet, which was estimated from aerial photographs. Site-specific data are not available for streambed thickness and hydraulic conductivity. These parameters were adjusted during the transient calibration and are assigned values of 1 foot and 1 foot/day, respectively, based on observations of streambed material and a representative hydraulic conductivity value for fine sand.

3.4.3.3 Surge Pond

The Surge Pond was also simulated using the River Package (**Figure 3-5**). Cells representing the Surge Pond were assigned stage elevations based on elevations measured at times of year similar to each model period (**Appendix C**). The surface water in the Surge Pond was assigned an elevation of 3,282.64 feet amsl in the 2014 steady-state model and an elevation of 3,283.39 feet amsl in the 2005

steady-state model. The surge pond elevation in the 2005-2007 transient model was varied for each stress period based on the average daily Surge Pond elevation estimated during each time period. The width and length of the River Package cells was based on the model cell dimensions. The bottom elevation of the River Package cells in the Surge Pond was extracted from a USGS digital elevation model (DEM) of the original ground surface. Site-specific data are not available for streambed thickness and hydraulic conductivity, but are area assigned based on estimates of 1 foot and 25 feet/day, respectively, based on observations of streambed material and a representative hydraulic conductivity value for silty-sand.

3.4.4 Barriers

MODFLOW's Hydraulic Flow Barrier (HFB) package was used to simulate the grout curtain in the STEP Main Dam and the Surge Pond Dam. This package implicitly represents a narrow (relative to the width of a model cell) feature in between model cells with a lower hydraulic conductivity than the adjacent model cells. The model code calculates the total conductance between the adjacent model cells with the user-specified width and hydraulic conductivity of the barrier feature, and the widths and hydraulic conductivities of the adjacent model cells. The grout curtain is represented as it was in the previous model with HFB features placed on both the upgradient and downgradient sides of the model cells coincident with the axis of the STEP Main Dam in Layers 2 through 5, based on design drawings. These HFB features are assigned a thickness of 5 feet and a hydraulic conductivity of 0.1 feet/day. For the Surge Pond Dam, the HFB features are assigned in Layers 2 through 3 with a thickness of 35 feet and a hydraulic conductivity of 1×10^{-2} feet/day.

3.4.5 Wells

Groundwater capture wells and water supply wells were represented using the Fracture-Well (FWL5) Package. The FWL5 Package is capable of representing wells that are screened across more than one model layer and calculates a single simulated water level in the borehole. These capabilities allow for more accurate simulation of wells with well screens that penetrate multiple layers.

Use of the FWL5 package can cause numerical instability but it has several characteristics that the standard Well Package does not have, including:

(1) The well pumping rates are automatically allocated between layers penetrated by the well screen. Assigned rates are based on the simulated water level in the FWL5 well, the simulated water level in each screened model cell layer, and the thicknesses and hydraulic conductivities of each screened model cell layer;

(2) When the level in the well drops below the bottom of the layer, the pumping rates are automatically reallocated to lower layers; and

(3) If the water level drops below the pumping level, the flow rate is decreased until the pumping level is maintained.

Locations of active pumping wells are shown on **Figure 3-8** (2005 steady-state model), **Figure 3-9** (2005-2007 transient model), and **Figure 3-10** (2014 steady-state model). **Table 2-13** lists capture wells and their assigned pumping rates for the 2005 and 2014 steady-state models. **Appendix J lists**

capture wells and pumping rates for the 2005-2007 transient model as well as the 2005 and 2014 steady-state models.

As discussed in **Section 2.6.6,** steady-state pumping rates for wells are generally set at 75 percent of reported pumping rates for July, August, and September of 2005 and 2014, with some exceptions. Reported pumping rates for several wells in two different areas below the STEP Main Dam increased appreciably starting in about January 2012, including 987D, 906D, 984D, 905D, 911D, 380D, 968D, 960D, and 961D. Analysis of the records indicates that water levels in these wells did not change appreciably in response to the reported higher pumping rates. Plots of pumping rates and groundwater elevations for these wells are included at the end of **Appendix E**. Discussions with Hydrometrics indicated the discrepancy may be due to a change in measurement methods, and that historic reported pumping rates were likely to be more representative of pumping rates after 2012 for these wells. To estimate a representative pumping rate for these anomalous wells, average rates were calculated from measured rates between January 2009 and December 2011, which is a period of relatively stable pumping rates.

Additional adjustments were made to simulated pumping rates for the 2014 steady-state model for wells 2024D, 991A, 993D, and 994A. Well 2024D was set to 75 percent of the average monthly pumping rate for September 2014 because the well was not pumping in July and August 2014. Pumping rates in well 991A, 993D, and 994A were all adjusted to 0 gpm because these wells were not pumped in September 2014, and only intermittently pumped in October 2014.

Monthly pumping rates in the transient model were set at 75 percent of the measured pumping rates for each month simulated. Transient model pumping wells and assigned rates are included in **Appendix J**.

3.4.6 Drains

The STEP Main Dam Toe Drain is represented in Layers 2 through 4 using the MODFLOW Drain Package, the same as in the previous model. The locations of the Drain Package cells in the model are shown on **Figure 3-5** (Layer 2) and **Figure 3-6** (Layer 3 and 4).

The Drain Package is a head-dependent boundary condition that is similar to a River Package boundary except it only allows water to move out of the model cell based on the difference between the groundwater elevation and drain elevation. A conductance term assigned to the drain cell restricts the flow rate exchange. The conductance is estimated by the following equation:

$$Conductance = KLW/D$$

Where:

K	=	*Hydraulic conductivity*
L	=	*Length of cell*
W	=	*Width of cell*
D	=	*Drain Bed Thickness*

Parameter specifications for the drain cells are included in **Appendix K**. Elevations for Drain cells were established based on design drawings (Bechtel, 1979) and were not modified from the previous versions of the model. Hydraulic conductivity and drain bed thickness were adopted from the original model development (Maxim, 2005) and were not modified for this modeling effort.

3.4.7 Recharge

Multiple recharge zones were established throughout the model domain to simulate background areal recharge from precipitation and seepage from water storage and process ponds. Recharge zones specified in the model are shown on **Figure 3-11**.

Recharge was assigned to the model using the MODFLOW Recharge Package. In the model, Recharge Package cells were assigned values representing net recharge (infiltration – evapotranspiration). Recharge areas were assigned rates based on the conceptual model (**Section 2.6.3**), and are summarized below.

3.4.7.1 Areal Recharge

Areal recharge to the model represents net infiltration or deep percolation (precipitation minus evapotranspiration and runoff) for areas not occupied by ponds. These areas include general background and also surface exposures of clinker. The distribution of areal recharge is shown on **Figure 3-11**. Areal recharge zones were assigned rates based on the conceptual model (**Section 2.6.3**).

Initially, background recharge was set at 1.5 percent of annual recharge for the steady-state models, and 1.5 percent of monthly precipitation for each monthly stress period for the 2005-2007 transient model. Recharge at exposures of clinker was set at 7 percent of annual recharge for the steady-state models, and 7 percent of monthly precipitation for each monthly stress period for the 2005-2007 transient model. Recharge estimates for the 2005 steady-state and 2005-2007 transient models were adjusted during calibration.

Final background and clinker recharge rates assigned in the model are based on the conceptual model water balance (**Section 2.6**) as follows:

- <u>2005 Steady-State Model</u>:
  - Background: 0.26 inch/year (approximately 1.35 percent of average annual precipitation).
  - Clinker: 0.79 inch/year (approximately 4 percent of average annual precipitation).
- <u>The 2005-2007 Transient Model</u>:
  - Background: constant rate of 0.22 inch/year, (approximately 1.5 percent of the average precipitation for the transient period).
  - Clinker: constant rate of 0.79 inch/year (approximately 5.3 percent of the average precipitation for the transient period).
- <u>2014 Steady-State Model</u>:
  - Background: 0.32 inch/year (approximately 1.5 percent of average annual precipitation).
  - Clinker: 1.49 inch/year (approximately 7 percent of average annual precipitation).

3.4.7.2 Stage I and II Pond Seepage

Net Infiltration through fly ash in SOEP and seepage of water from STEP were simulated using the Recharge Package. Seepage from the following ponds (described in **Section 2.3.4** and **Section 2.6.2**) were assigned using different recharge zones: (1) Cell E, (2) Cell A, (3) Old Clearwell, (4) Evaporation Pad, (5) Cell B/New Clearwell, and (6) Cell D. The areas of recharge zones reflecting pond seepage, shown on **Figure 3-11**, were created by delineating the surface area of the pond using aerial photographs.

Initial recharge estimates were assigned to the model based on water budget estimates (**Section 2.6**) and were adjusted during calibration. Final calibrated recharge rates for the SOEP and STEP ponds are discussed in **Section 4.0**.

Cell B, Cell D and the Passive Evaporation System north of Cell A were constructed between the 2005 and 2014 steady-state simulated periods. Recharge for zones representing these features were assigned background rates in the 2005 simulation.

3.5 AQUIFER PARAMETERS

Aquifer parameters assigned in the model consist of hydraulic conductivity, aquifer storage, and effective porosity. Parameter values were assigned to model cells based on the hydrostratigraphy of the subsurface delineated for the conceptual model described in **Section 2.1.4**.

3.5.1 Hydraulic Conductivity

Horizontal hydraulic conductivity (K_h) zones were developed using information obtained from lithologic logs, literature values, aquifer tests, and observed groundwater flow patterns. Geometric mean hydraulic conductivity values from field tests collected for the various hydrostratigraphic units and summarized in **Section 2.1.4** were assigned to the various hydrostratigraphic units in the model as initial estimates. Zones of higher hydraulic conductivity were assigned to alluvium and sandstone bedrock; zones of lower hydraulic conductivity were assigned to finer-grained bedrock (e.g., siltstone and claystone).

The vertical hydraulic conductivity (K_v) of sedimentary rocks and unconsolidated deposits are generally less than the horizontal hydraulic conductivity. This phenomenon is caused by the original sediments being deposited in horizontal layers and vertical compaction of sediments by the weight of overlying deposits. Vertical hydraulic conductivity is commonly expressed as the ratio of horizontal to vertical hydraulic conductivity (K_h:K_v). Initial model values for the K_h:K_v ratio were set at ranges between 10:1 and 100:1 based on the hydrostratigraphic unit.

Hydraulic conductivity zones representing lithologic units were further subdivided during calibration and the values assigned to these zones were adjusted within the measured ranges in order to meet calibration goals. The final calibrated hydraulic conductivity is described in **Section 4.0**.

3.5.2 Aquifer Storage

Steady-state simulations do not involve aquifer storage parameters. For transient groundwater flow simulations, the movement of groundwater to and from storage in aquifer materials must be considered.

Storage of groundwater in aquifer materials takes two forms: (1) specific yield is a property of unconfined aquifers, and (2) storativity is a property of confined aquifers (specific storage multiplied by thickness).

Specific yield represents the drainable portion of porosity at the water table. Specific yield, values assigned to the model were based on material properties described in the available well logs and on reported literature values. Specific yield from the literature for various geologic material include the following:

- Gravelly Sand: 0.2-0.35 (Fetter, 1994);
- Silt: 0.03-0.19 (Fetter, 1994);
- Clay: 0-0.05 (Fetter, 1994); and
- Siltstone: 0.009-0.327 (Morris and Johnson, 1967).

Specific storage represents the volume of water removed from a unit volume of aquifer material per unit decline in groundwater hydraulic head due to expansion of the matrix of grains in a sedimentary rock or unconsolidated deposits from the release of groundwater pressure. Specific storage multiplied by thickness gives storativity, which for confined aquifers is 0.005 or less (Fetter 1994). Storativity for units at the site are provided in **Table 2-1** which lists storativity for alluvium as 0.0003 and for Sub-McKay as 0.0008.

Initial values of specific yield and specific storage were assigned to each hydraulic conductivity zone and adjusted during calibration. The calibrated storage parameters are described in **Section 4.0.**

3.5.3 Effective Porosity

Particle tracking (presented in **Section 6.0**) requires assignment of effective porosity values. The range of values for effective porosity based on literature for the various lithologic units are presented in **Table 3-1.** The calibrated parameters are described in **Section 4.0.**

Table 3-1. Summary of Effective Porosity Values from Literature

	Effective Porosity Range	Effective Porosity Reference
Gravelly Sand	0.2-0.35	Domenico & Schwartz (1990)
Silt	0.01-0.3	Domenico & Schwartz (1990)
Clay	0.01-0.2	Domenico & Schwartz (1990)
Siltstone	0.01-0.35	Domenico & Schwartz (1990)
Coal	0.008-0.094	Brown and Parizek (1971)
Sandstone and siltstone	0.01-0.4	Domenico & Schwartz (1990)

3.6 MODEL CHANGES SUMMARY

The conceptual model described in **Section 2.0** provides the foundation for the development and parameterization of the current SOEP and STEP numerical model. The development of the current SOEP and STEP model was performed using the previous SOEP and STEP model documented

(NewFields, 2014) and applying refinements based on the updated conceptual model as discussed in **Section 2.0**. The primary changes incorporated in the current SOEP and STEP model include the following:

- Domain: The model domain was expanded to the north of Stocker Creek and to the east side of East Fork Armells Creek;
- Layer Elevations: As described in **Section 3.3**, model layer elevations were adjusted in several portions of the model based on lithologic contacts from well logs for new wells installed since 2010 and to better represent hydrostratigraphy and hydraulic communication as within a sandstone layer hosting capture well 958D;
- Recharge: Additional recharge zones were added to represent the Evaporation Pad (located at the just north of Cell A), Cell D, and Clinker outcrops;
- General Head Boundaries: GHB Package cells were added to Layer 5 and 6 to represent underflow flowing into and out of the model domain;
- Pumping Rates: Pumping rates were adjusted to reflect new estimates of pumping rates;
- Pumping Wells: Additional pumping wells were added to the model to reflect expansion of the capture system between 2010 and October 2014;
- Calibration Data: The model was calibrated to new data sets (including new pumping test results), and datasets were revised to represent October 2005 and 2014 steady-state conditions; and
- East Fork Armells Creek Alluvium: Alluvium along the creek was changed to be simulated as fine-grained sediments overlying and coarse-grained sand and gravel.

4.0 MODEL CALIBRATION

Model calibration involves finding a combination of boundary conditions, input parameters, and stresses that generate head and flux values throughout the model that match field-measured head and flux values and achieve the calibration goals, as outlined below. Groundwater model development and calibration were conducted in general accordance with standard industry practices, such as described in Anderson et al. (2015).

Following refinement of the model framework and boundary conditions and assignment of initial input parameters (**Section 3.0**), the model was calibrated to provide confidence in its ability to simulate groundwater flow under different conditions and to meet project objectives. The calibration process required first establishing a set of calibration targets and goals. Model inputs were then adjusted iteratively within appropriate ranges based on measured data to achieve a reasonable match between observed and simulated target values. The quality of the match was judged using both quantitative and qualitative methods.

The model calibration process involved adjusting uncertain input parameters within reasonable ranges to reduce the difference between measured and simulated target values. It should be noted that achieving calibration does not guarantee the set of input parameters selected is unique and that other plausible inputs would not achieve similar calibration results. However, calibration and verification of the model to several independent and different sets of both steady-state and transient target data increases confidence in the model's capability to simulate groundwater flow under a variety of aquifer conditions.

4.1 DEVELOPMENT OF CALIBRATION TARGETS AND DATA SETS

Both qualitative and quantitative targets were developed as part of the calibration process. Qualitative targets include potentiometric surface maps that were developed based on measured groundwater elevations, hydrographs of groundwater elevations over time, and time-drawdown plots from aquifer tests.

Quantitative targets used to calibrate the model include measured groundwater elevations, estimated underflow into and out of the model domain, and net gains and losses in East Fork Armells Creek. The following independent steady-state and transient hydrologic data sets were used to establish calibration targets:

- Heads (groundwater elevations) and fluxes for the period of October 2005 (Steady-State);
- Pumping Tests conducted at wells 958D and 966A (Transient);
- Time variant heads and fluxes measured between November 2005 and December 2007 (Transient); and
- Heads and fluxes for the period of October 2014. Head targets were supplemented with additional groundwater level data measured at other times to provide greater spatial coverage (Steady-State).

4.1.1 2005 Steady-State Calibration Data Set

Head targets for the 2005 steady-state model were established from water levels measured primarily in October 2005. A total of 44 head targets were used in the 2005 steady-state model, which are listed in **Appendix L**.

Some potential target wells are screened across multiple layers. Data from wells constructed in this fashion were problematic because downward gradients simulated by the model often created head differences as much as 10 feet between the layers. In Groundwater Vistas ®, a target well is assigned to a single model layer. If the user wants to assign a target well to two different layers, the target has to be assigned as two different wells (one in each layer) and the model will provide two separate head outputs reflecting the simulated heads in the different layers. To determine the residual head difference between measured head values, a vertical interpolation must then be conducted to calculate a single head output at the targets location. Due to the large variations in heads between the bedrock layers at various locations and the uncertainty regarding vertical interpolation, various wells screened across more than one bedrock layer were not used as targets. All alluvial wells screened across multiple layers representing alluvium were used as targets because there is little to no head difference between the vertical layers in the alluvium.

Estimated fluxes in the water budget for October 2005 (**Table 2-6**) were used as flux targets for the 2005 steady-state model. The water budget includes estimates of groundwater underflow, pond seepage, background areal recharge, groundwater extraction (from drains and wells), and net flow loss and gain estimates between East Fork Armells Creek and Stocker Creek and the groundwater system.

In addition to the target head and flux data, the 2005 potentiometric surfaces discussed in **Section 2.4.1** were used to qualitatively evaluate model calibration based on the observed closeness of fit between simulated and observed potentiometric surfaces maps.

4.1.2 Transient Calibration to Aquifer Test Data

Two pumping tests performed at the site were simulated using the transient model in order to provide a check on the ability of the model to replicate groundwater responses under conditions different from the steady-state and transient models. Several pumping tests have been performed in the SOEP and STEP area, as summarized in **Section 2.1.4**, and all of these tests were evaluated as potential calibration targets. Aquifer test results were selected for calibration based on the test well location, reliability of the pumping test data, and availability of observation well data, which are often more representative of head values in the aquifer than those measured in the pumping well.

Pumping tests were excluded from modeling consideration if: 1) the test was a single-well test; 2) observation wells were screened over multiple model layers; 3) significant drawdown was not observed in observation wells, or 4) the data appear anomalous. Pumping tests conducted at wells 2024D and PW704D-2 were initially simulated, but ultimately not used for calibration due to uncertainty in measured pumping rates and inconsistencies in aquifer test results.

Aquifer tests performed on wells 958D and 966A were used for transient calibration, as discussed below.

Well 958D

Well 958D is located on the dike between the Cell A and Cell E (**Figure 2-1)**. Wells 975D and 902D located approximately 1,510 and 1,240 feet north of 958D, respectively were used as observation wells during the pumping test. A transient simulation of the pumping test was performed using one stress period representing the pumping period from May 21 to May 31, 2010. Pumping of well 958D was simulated at 5.9 gallons per minute (gpm). Wells 975D and 902D were used as targets for the transient calibration and simulated drawdown over time was recorded and compared to plots of measured drawdown from the test.

Well 966A

Well 966A is located within the footprint of the SOEP (**Figure 2-1**) and is completed beneath Fly Ash in alluvium and upper few feet of bedrock. Observation well data for two wells (946 and 976P located approximately 15 feet and 10 feet from well 966A, respectively) were available for the well 966A pumping test. Well 946 is screened in the alluvium beneath the Fly Ash and well 976P is screened vertically above 966A in the Fly Ash. A transient simulation of the pumping test was performed with 966A pumped for 3.9 days at a constant rate of 2.5 gpm. Wells 946 and 976P were used as targets for the transient calibration and simulated drawdown over time was recorded and compared to plots of measured drawdown from the test.

4.1.3 November 2005 – December 2007 Transient Calibration Data Set

The transient calibration period includes the time when pumping of several groundwater capture wells was initiated (including 960D, 961D, 963D, 968D, and 970D, located in a line approximately 500 feet downgradient of the STEP Main Dam, **Figure 2-43**) and also when a breach of the STEP Clearwell liner occurred followed by subsequent repair of the breach. The calibration data set for the 2005-2007 transient model included head targets from measured water levels obtained from November 2005 through December 2007. The data set was matched qualitatively by comparing measured and simulated hydrographs at monitoring points for the time period covered by the model.

A total of 87 target locations with a total of 994 target head values were used in the 2005-2007 transient model for calibration. Two additional target locations (wells 361D and 362D) were used for qualitative calibration of the transient model, although these wells are screened across layers exhibiting a steep vertical hydraulic gradient. These wells were not used for quantitative calibration for the steady-state calibration models.

4.1.4 2014 Steady-State Calibration Data Set

The head targets for the 2014 steady-state model were established from water levels measured primarily in October 2014. The water level data set was taken from a time which exhibited relatively low precipitation and fairly stable groundwater elevations when transient stresses were at a minimum. A comprehensive synoptic groundwater level data set from October 2014 was used to develop a calibration data set representative of that time frame.

The head target data set was augmented with additional groundwater level data measured at other times in 2014 to provide greater spatial coverage. As discussed in **Section 2.4.1**, the use of water levels from

a time period different from other wells is typically avoided, but in this case these were the only data available in certain areas of the model domain. While these water levels may introduce some uncertainty in the calibration in the areas they represent due to seasonal fluctuations, the variation is likely to be small and these provide important calibration point locations.

A total of 116 head targets were used in the 2014 steady-state model. As discussed in **Section 4.1.1,** target wells screened across multiple layers must be assigned to only one layer. Due to the large variations in heads between the bedrock layers at various locations and the uncertainty regarding vertical interpolation, various wells screened across more than one bedrock layer were not used as targets. All alluvial wells screened across multiple layers representing alluvium were used as targets because there is little to no head difference between the model layers representing alluvium, so assigning these targets to a single layer introduces minimal error. **Appendix M** presents the observed head targets and the dates of the measurement.

The calculated fluxes associated with the water budget for October 2014 (**Table 2-6**) were used as flux targets for the 2014 steady-state model. The water balance included estimates of groundwater underflow, pond seepage, background areal recharge, groundwater extraction (from drains and wells), and net flow loss and gain estimates between East Fork Armells Creek and Stocker Creek and the groundwater system. A description of the components of water balance for October 2014 is discussed in **Section 2.6**.

In addition to the target head and flux data, the 2014 potentiometric surfaces discussed in **Section 2.4.1** were used to visually calibrate the observed closeness of fit between simulated and observed potentiometric maps.

4.1.5 Calibration Goals

A set of both quantitative and qualitative criteria was established as goals to assess how well the model was calibrated. Statistics of calibration residuals, or the difference between the model simulated and the observed target values, for each head target were used as goals, along with boundary fluxes and qualitative measures. Steady-state and transient goals for the steady-state models are summarized below.

<u>Steady-State Model Goals</u>

- The absolute residual mean for head targets (average absolute value of the difference between simulated and target head values) should be less than 2.0 feet (Quantitative);
- The residual mean for head targets (average difference between simulated and target head values) should be close to zero (Quantitative);
- The residual standard deviation divided by the range in head values should be less 5 percent (Quantitative);
- The absolute value of residuals should be ≤ 5 feet (Quantitative);
- Simulated groundwater flux into and out of the model along East Fork Armells Creek should be within the range of flux estimated as part of the conceptual model water balance (Quantitative); and

- Visual observations should reveal that the simulated and observed potentiometric maps are a close fit (Qualitative) taking into account the spatial distribution of observed data points used to develop the potentiometric surface maps.

Transient Model Goals

- Residual statistics should fall within criteria established for steady-state calibration described above (Quantitative); and
- Hydrographs of simulated groundwater elevations vs. time and drawdown vs. time should match those based on field-measured values in timing and magnitude of water level changes (Qualitative).

4.2 CALIBRATION PROCESS AND RESULTS

During calibration, different input parameters are varied iteratively within a plausible range of values to minimize residuals, which are the difference between simulated and target values. Calibration was achieved using both manual and automated techniques to vary input parameters based on field measurements and literature values described in **Section 2.0**. Results of each calibration simulation were then evaluated to determine if the input parameter adjusted during that run achieved a better or worse match to calibration targets. Calibration results were evaluated using both quantitative and qualitative methods and completed iteratively between the transient and steady-state models. Residuals and residual statistics were calculated after each model run and used as a measure of the overall match between simulated and observed conditions.

As discussed above, qualitative methods applied to the calibration process included visually comparing potentiometric surface maps or hydrographs generated by the model to those based on target values. The quality of the match through application of these comparisons was then judged by the modeler (Anderson et al., 2015).

More emphasis was placed on evaluating measured heads and measured stream gains and losses and pond seepage during calibration than on estimated fluxes, such as groundwater underflow. Changes made to non-transient inputs that improved calibration statistics in one of the four calibration schemes were subsequently applied to the model for use in the other three calibrations. If the changes improved calibration in all schemes evaluated, the changes were retained and the calibration process continued. Particle tracking was performed intermittently to confirm particles released in the pond area (contaminant source area) traveled to areas of known contamination and did not travel to areas known to be free of contaminants.

Parameter Estimation (PEST) techniques (Doherty, 2005) were used to help with automated calibration. PEST allows the modeler to test the best combination of a range of values for a single parameter or multiple parameters based on the assigned range of values. PEST uses quantitative statistics to evaluate the best combination of parameters while all other parameters in the model remain the same. When PEST was applied in one of the models on a single or set of parameters and revised values were shown to be preferable, these values were tested in the other models and retained if changes improved calibration in all schemes evaluated.

Input parameters that were varied during calibration (listed in order of priority to model calibration) were as follows:

- Hydraulic Conductivity (varied within ranges described for each lithostratigraphic unit [See **Section 2.1.4**]);
- Pond Seepage (varied within ranges estimated in the water balance discussion [see **Section 2.6**]);
- Background Recharge (varied within estimated range provided in the water balance discussion [see **Section 2.6**]);
- Conductance of Head-Dependent Boundaries (varied with changes for the assigned hydraulic conductivity of the adjacent cell);
- Storage (only adjusted in transient calibration) (varied within ranges reported from aquifer tests [**Appendix A**] and literature values for similar lithologies); and
- Stage in the East Fork Armells Creek.

The most frequently adjusted parameter during steady-state calibration was hydraulic conductivity. Seepage rates for single-lined STEP cells (A, C, and Old Clearwell) were also frequently adjusted within reasonable ranges. Elevations of river cells were initially assigned as discussed in **Section 3.4.3**. River stage values for Reach 1 were adjusted during calibration by flattening the gradient along the upstream portion of this reach to decrease flow out of and increase flow into the model along this reach (see **Section 4.2.5.2** below). During transient calibration, recharge rates and storage parameters were adjusted most frequently with fewer adjustments to hydraulic conductivities other than adjustments made as a result of steady-state calibration. Particle-tracking was periodically performed to check the match between simulated and observed movement of process pond-affected groundwater.

4.2.1 Calibrated Parameter Distributions

This section describes the distribution of parameters that remain constant in all model calibration periods. The distribution of recharge, which varies for each calibration period, is described in **Sections 4.2.2**, **4.2.4**, and **4.2.5** below.

Figure 4-1 through **Figure 4-7** show the final calibrated distribution of horizontal hydraulic conductivity zones for Layers 2 through 8, respectively**.** **Appendix N** presents the horizontal and vertical hydraulic conductivity values and corresponding lithologic unit for each of these zones. Calibrated hydraulic conductivity values are the same for all model calibration periods. Final calibrated hydraulic conductivity values generally fall within the estimated range of values for the corresponding hydrostratigraphic units described in **Section 2.1.4**. The hydraulic conductivity distribution in Layer 4 downgradient (east) of the STEP dam is highly detailed and sometimes varies by orders of magnitude over short distances. Hydraulic conductivity values from pumping test analyses for specific pumping wells were honored in the model. In specific areas, low hydraulic conductivity zones were placed between capture wells to simulate the lack of hydraulic communication between some wells as part of the transient calibration process.

Table 4-1 presents a comparison of the hydraulic conductivity estimates established as the possible range of values for the various hydrostratigraphic units, based on onsite hydraulic tests and literature based values, to the final calibrated hydraulic conductivity values assigned to the respective units in the model.

Ratios of horizontal to vertical hydraulic conductivity (K_h:K_v) in the model vary considerably. The K_h:K_v ratios used in most of the model range from 1,000:1 in unconsolidated sedimentary deposits (e.g., alluvium) to 500,000:1 for deeper bedrock, although there are some areas of the model where the ratio is as low as 1:1. The K_h:K_v ratios incorporated into the model are typically supported by literature values. For example, Todd (1980) reported K_h:K_v can range from 10:1 to 1,000:1 in alluvium. Anisotropy ratios of shales can range from 50:1 to 5,000:1 depending on the scale measured (Cosan et al., 1994), and are also reported to range from 1,220:1 (formations with thick and frequent shales) to 100:1 (sandstone formations with short thin and frequent shales; Burton and Wood, 2013).

Table 4-1. Final Calibrated and Measured Horizontal Hydraulic Conductivity Values

Aquifer Material	Calibrated Horizontal Hydraulic Conductivity of Zones Representing Various Aquifer Materials		Hydraulic Conductivity as Summarized in Table 2-1	
	Min	Max	Min	Max
Alluvium	0.5	200	0.00007	492
Interburden	0.1	5	0.02	39
McKay Coal	1	5	0.01	9.3
Sub-McKay	0.001	100	0.01	242

In the Fort Union Formation, vertical anisotropy is greatly influenced by bedding planes and the sedimentary processes that formed inter-fingered sandstone, shale, mudstone and coal strata. The K_v of a given section of the Fort Union Formation is primarily controlled by the units in that section with the lowest K_v and its degree of lateral continuity, whereas the K_h will be controlled by the higher permeable units. Nicklin Earth and Water (2014) estimated K_h:K_v in some of the Fort Union interbedded sandstone and mudstone units of as high as 2,000,000:1. However the presence of vertical fractures can greatly influence the anisotropy of the bedrock layers and reduce the K_h:K_v ratio.

Vertical anisotropy will typically vary between different hydrostratigraphic units. The Sub-McKay units have a range of K_h, dictated by whether there are greater amounts of sandstone or shale/mudstone. It was necessary to assign lower K_v in order to match measured vertical hydraulic gradients between the shallow and deep Sub-McKay. The steep vertical gradients may be explained by the presence of thicker, more continuous low permeability layers (shale/mudstone) in the deeper Sub-McKay and thicker more continuous packages of sandstone in the shallower Sub-McKay.

Calibrated storage values for the transient model (**Table 4-2**) are within estimated ranges of values (see **Section 3.5.2**). Final calibrated storage values applied are the same for all model calibration periods. During calibration of the groundwater model, bedrock and alluvium were assigned specific yield values of 1 percent and 14 percent, respectively. During the transient calibration the specific yield of alluvium in the drainage located in the vicinity of well 977A, and beneath a portion of the Surge Pond, was lowered to 2 percent to achieve a better match to hydrographs for wells in those areas. Fly Ash in the Stage I Pond was assigned a specific yield of 2.5 percent.

Both bedrock and alluvium were assigned specific storage values of $5x10^{-5}$ and $5x10^{-4}$, respectively. Fly ash in the Stage I Pond was assigned a specific storage of $1x10^{-4}$. Specific storage was reduced to $5x10^{-6}$ near wells 969D and EAP-411 during transient calibration to better match the pumping response in those wells. In the area of well 966A, the specific storage was reduced to $5x10^{-6}$ to better reflect the results of the pumping test conducted at that location. During calibration specific storage in two zones in Layer 6 near well 958D were reduced to $7x10^{-7}$ and $3x10^{-6}$ to achieve a better match to heads.

Table 4-2. Final Calibrated Storage Parameter Values

Unit	Specific Storage (unitless)	Specific Yield (unitless)
Alluvium	5×10^{-4}	2-14%
Fly Ash	1×10^{-4}	2.5%
Bedrock	5×10^{-5}- 7×10^{-7}	1-10%

As described in **Section 3.4.3**, the conductance is calculated from the stream width, length, hydraulic conductivity, and thickness. A uniform hydraulic conductivity and streambed thickness were used for streambed conductance were used. Streambed thickness for both streams is estimated to be 1 foot. The calibrated hydraulic conductivity of the streambed in each river cell in East Fork Armells Creek and Stocker Creek is 50 feet/day and 1 foot/day, respectively.

The River Package conductance for cells simulating the Surge Pond was adjusted during model calibration until there was a reasonable match with estimated seepage rates (**Table 2-6, Section 2.6**). The length and width of the conductance term are fixed. The thickness and hydraulic conductivity of the bed are unknown. The final calibrated value of the hydraulic conductivity divided by the thickness of the lakebed is 25 day^{-1}. This value of this portion of the conductance term was applied to all cells in all model calibration periods.

The calibrated hydraulic conductivity of the drain cells representing the toe drain at the STEP Main Dam is specified in the model at 100 feet/day. Calibrated hydraulic conductivities for the GHBs are the same as the hydraulic conductivity of the surrounding aquifer materials. The calibrated drain cell and GHB hydraulic conductivity developed were applied to all model calibration periods.

4.2.2 2005 Steady State Calibration

A total of 28 pumping wells were simulated as actively pumping in the 2005 steady-state model. The pumping rates for these wells were established as the average pumping rate for August-October of 2005 as presented in **Section 2.6.6. Table 2-13** and **Appendix J** summarizes the pumping rates used in the model.

Recharge rates used in the 2005 steady-state model are presented on **Figure 4-8**. The rates ranged from 6×10^{-5} to 8.18×10^{-4} feet/day. These rates, applied within the recharge zones shown on **Figure 4-8**, resulted in an inflow within the range of estimated inflow for background recharge and pond seepage.

Appendix L contains calibration statistics resulting from the 2005 steady-state model, based on 44 head targets. All head target statistics and the other general components of the water balance met the

steady-state model calibration goals. Further, visual comparison of the simulated and observed potentiometric maps show that, in general, groundwater flow directions and gradients were similar.

4.2.2.1 2005 Calibration to Head Data

The calculated residual mean of target head values for all target wells was -0.63. A small residual mean indicates model heads are not biased too high or too low (Anderson et al., 2015). The absolute residual mean of the target head values was 1.81 feet, which meets the calibration goals of less than 2 feet. The residual standard deviation divided by the range of observed heads is 1.3 percent. Many practitioners believe this statistic should be less than 10 percent and the calibration goal was less than 5 percent. The maximum residual was 4.65 feet and the minimum residual was -4.83 feet, which is within the goal of ± 5 feet. **Figure 4-9** is a plot showing simulate vs. observed target values that are evenly distributed around a 1:1 line, demonstrating there is no groundwater elevation bias (Anderson et al, 2015) and that the model is well-calibrated.

Figure 4-10 through **Figure 4-16** are maps showing the simulated potentiometric surfaces for Layers 2 through 8, for the 2005 steady-state calibration. Visual comparison of the computed potentiometric contours to those based on field measurements (**Figure 2-9** through **Figure 2-11**) indicates a good match between simulated and observed heads and gradients with only slight variations visible between the observed and simulated potentiometric surfaces. For example, the observed and simulated shallow potentiometric surfaces vary slightly in flow direction and gradient in the west central portion of the model. However, the observed groundwater elevations in this area are sparse and hence flow directions and gradients based on observed data are somewhat uncertain. Simulated groundwater elevation contours for Layer 5 match the potentiometric surface contours based on target values relatively well (**Figure 2-9**).

Residuals at each target location are illustrated on **Figure 4-10** through **Figure 4-16**, with positive (blue) values indicating the simulated head is less than the observed head and negative (red) values indicating the simulated head is greater than the measured value. In most areas positive and negative residuals shown on these figures are randomly distributed without large areas of spatial bias. **Figure 4-10**, **Figure 4-12**, and **Figure 4-13** indicate that the 2005 simulation over-predicts heads east of the SOEP Dam in Layer 2, on the north and west side of the SOEP in Layer 4, and north and east of the STEP Main Dam in Layer 5, respectively.

Table 4-3 presents residual statistics by layer. Calibration statistics indicate that some model layers exhibit some spatial bias. Bias refers to the tendency to over- or under-estimate the value. Negative values indicate the heads are biased high and positive residuals indicate heads are biased low. Based on mean residuals, Layers 2, 4, 5, have slightly over-estimated groundwater elevations, while Layers 3 are slightly underestimated.

Table 4-3. 2005 Calibration Statistics by Layer

Layer	Absolute Residual Mean	Residual Mean
Layer 2	1.50	-1.50
Layer 3	1.63	0.77
Layer 4	1.65	-0.95
Layer 5	1.83	-1.75
Layer 7	3.19	1.94

* Layers 6 and 8 only have one target

4.2.2.2 2005 Calibration to Flux Data

The components of the 2005 steady-state water balance were compared to the components of the estimated water budget to ensure the model simulation incorporated the appropriate rates of flux. **Table 4-4** presents the estimated water balance along with the corresponding simulated water balance. The estimated water balance was also presented in **Table 2-6** and the basis for the estimates discussed in **Section 2.6**. All the simulated flux values fall within the estimated ranges with the exception of discharge to Stocker Creek, which is slightly under predicted but close to the calculated minimum. **Appendix O** contains the groundwater model water balance resulting from the calibrated 2005 steady-state model.

East Fork Armells Creek gains and losses were not measured in 2005 during the simulated time period and, therefore simulated gains and losses in the creek were not used as a basis for calibration for the 2005 model. **Table 4-5** presents the 2005 steady state simulated flux from groundwater to East Fork Armells Creek.

Table 4-4. Summary of Estimated and Simulated Water Balance for 2005

	2004-2005						Simulated Groundwater Balance	
	Min (ft^3/d)	Max (ft^3/d)	Estimate (ft^3/d)	Min (gpm)	Max (gpm)	Estimate (gpm)	Simulated (ft^3/d)	Simulated (gpm)
Inflows								
Underflow In	1,566	4,039,233	73,362	8	20,982	381	52,206	271
Surge Pond Seepage	5,103	51,031	16,137	27	265	84	13,500	70
Infiltrating Background Recharge	8,522	14,203	11,362	44	74	59	10,232	53
Infiltrating Clinker Recharge	1,014	7,095	4,054	5	37	21	1,949	10
SOEP Infiltrating Recharge	2,493	4,155	3,324	13	22	17	2,537	13
STEP Pond Seepage	2,127	4,418	3,273	11	23	17	2,598	14
Total IN	**20,825**	**4,120,134**	**111,512**	**108**	**21,402**	**579**	**83,023**	**432**
Outflows								
Underflow Out	664	400,356	57,535	3	2,080	299	51,230	266
Discharge to East Fork Armells Creek	2,588	12,213	7,401	13	63	38	8,179	43
Discharge to Stocker Creek	295	2,951	1,623	2	15	8	172	1
Groundwater Extraction	13,926	27,852	20,889	72	145	109	23,153	120
Total OUT	**18,491**	**445,408**	**88,975**	**96**	**2,314**	**462**	**82,734**	**430**

Notes: ft^3/d = cubic feet per day; gpm = gallons per minute

Table 4-5. 2005 Steady State Simulated Flow Into and Out of East Fork Armells Creek

Model Reach	0	1	2	3	4	5	6	7
Stream Reach (Station Nos.)	(Model Boundary to AR-1)	(AR-1 to AR-9)	(AR-9 to AR-8)	(AR-8 to AR-7)	(AR-7 to AR-6)	(AR-6 to AR-11)	(AR-11 to AR-10)	(AR-10 to Model Boundary)
Simulated Flow to East Fork Armells Creek from Groundwater (gpm)	46	-19	-15	45	-26	17	7	-12

Note: Negative values indicate a loss in streamflow

The estimated average groundwater capture rate estimated for July through September 2005 was 123 gpm. The simulated extraction was slightly lower than this (120 gpm) due to MODFLOW SURFACT's FWL5 Package automatically reducing flow rates to a few wells.

4.2.3 Transient Calibration to Aquifer Test Data

Figure 4-17 and **Figure 4-18** display simulated and observed drawdown during testing of wells 958D and 966A, respectively. Simulated drawdown at observation wells 902D and 975D for the 958D aquifer test match the magnitude of measured drawdown at the end of the test. However, the simulated timing of drawdown early in the test (less than 1 day) does not match the observed drawdown for well 975D and insufficient data for well 902D did not allow for matching of early time data. Simulated drawdown at observation well 946 for the 966A aquifer test compares well with the timing and magnitude of measured drawdown. Simulated drawdown at observation well 967P, which is completed in a shallower layer than the pumping well (966A), underestimates the drawdown. As shown on **Figure 4-17**, the pumping test under-predicts the drawdown in observation well 976P. This lack of observed response may be a result of the coarse nature of the model layering and geometry compared to the proximity of the pumping well (966A) and observation well (976P); well 976P is located in the cell directly above the model cell assigned to the pumping well.

4.2.4 Long-Term Transient Calibration

The long-term transient simulation included 27 stress periods representing the 26 months from November 2005 through December 2007. The period representing November 2005 was split into two stress periods to better simulate the initiation of groundwater capture by the 960-Series capture system in mid-November of that year. The Automatic Time Stepping (ATO) Package was used to automate the most efficient time stepping to reduce model run times. The 2005 steady-state model provided the initial conditions for the November 2005 through December 2007 transient model. Model inputs were adjusted in an iterative manner to improve the match between hydrographs based on field-measured data and those simulated by the model.

As discussed in **Section 3.4.5**, pumping wells were simulated using a 75% adjustment of the measured average monthly pumping rates from the period between November 2005 and December 2007. **Appendix J** shows measured and simulated pumping rates for all capture system wells and other

pumping wells during this period. Pumping at multiple capture wells was initiated in November 2005 (stress period 2 in the model). In addition, Surge Pond stages and river stages were varied to reflect the temporal head changes observed at wells located in proximal to East Fork Armells Creek and Stocker Creek. Monthly stage data for East Fork Armells Creek were not available; therefore, head changes at well 918A were used to reflect changes in river stage as described in **Section 3.4.3**.

To calibrate the various hydrographs to changes induced from both pumping and recharge, pumping influences were first determined by maintaining constant recharge in the area. Once the model was run with constant recharge for an area, pumping influences could be detected in hydrographs. Transient recharge was then introduced in areas where, by doing so, the match to water level increases and decreases in the hydrographs was improved. An attempt was made to match both the timing and magnitude of observed water level changes.

In addition to simulating seasonal effects from regional recharge fluctuations, various other known recharge events occurred that induced stress on the aquifer. In April 2007, a breach developed in the liner of the Old Clearwell when struck by a barge, resulting in a release of an unknown quantity of pond water and an increase in groundwater elevations in several surrounding wells. The northern section of the Old Clearwell was simulated with low recharge to represent its intact liner and, starting from April 2007, the breach was simulated by an increase in recharge at the northern portion of the Old Clearwell. The liner was repaired in November 2007 and the modeled recharge was reduced to a rate of 0.05 feet/day after that point in time. **Appendix P** lists the calibrated monthly recharge values used for the 2005-2007 period for all the zones shown on **Figure 3-11.** Overall, three of the 12 recharge zones were adjusted to simulate transient recharge. **Table 4-6** lists transient events and the model design to simulate the event.

Table 4-6. 2005-2007 Transient Events and Associated Model Design

Stress Period(s)	Starting Date of Stress Period	Transient Event	Model Design
All	---	Fluctuations in stage of Surge Pond	Daily readings of Surge Pond stage averaged over each model stress period assigned to River Package cells representing Surge Pond
All	---	Fluctuations in stage of East Fork Armells Creek	Observed water levels in well 918A used to vary stage assigned to River Package cells representing East Fork Armells Creek
All	---	Fluctuations in stage of Stocker Creek	Observed water levels in well 975A used to vary stage assigned to River Package cells representing Stocker Creek
12-27	Sept-06	Cell B was filled with water with subsequent increases in water levels in wells around Cell B	Seepage from construction of Cell B (Several defects were discovered ranging from minor punctures to a bad seam weld; these were repaired in 2007 [Hydrometrics 2016]).
11-18	Aug-06	Increase in pumping below STEP Main Dam and reported water levels in hydrographs did not show a decline.	Slight increase in pond seepage from the STEP Clearwell
19-25	Apr-07	Clearwell barge causes tear in liner at southern edge of the STEP Clearwell	Large Increase in seepage through the southern edge of the STEP Clearwell
25	Oct-07	Repairs made to tear in STEP Clearwell liner	Seepage through the southern edge of the STEP Clearwell reduced

Simulated and field-measured hydrographs are displayed on **Figure 4-19** through **Figure 4-25** for the layers with observed data (Layers 2 through 8). The degree of fit was assessed primarily qualitatively by visual assessment of the match between simulated and observed hydrographs. When reviewing these hydrographs, the match of overall trends (increasing/decreasing) and the match to the short-term transient Clearwell liner tear and subsequent pump-back operation were judged as most important. Simulating the observed hydraulic responses in the deeper layers (7 and 8) was viewed as less important. However, the overall match of average value was also considered and the number of measured groundwater elevation measurements at each site was taken into account.

Evaluation of hydrographs below the STEP Main Dam (which is influenced by pumping) shows the model is capable of simulating a reasonable match in timing and magnitude of pumping trends in the area. The area east of the STEP Main Dam appears to show hydraulic trends influenced in part by the Surge Pond stage fluctuations and pumping below the STEP Main Dam. The model also is capable of simulating a reasonable match in the timing and magnitude of hydraulic responses in this area.

Evaluation of hydrographs near the Surge Pond reveals changes in the Surge Pond water level elevations induce a hydraulic response in the aquifer locally. This response is controlled by a combination of hydraulic conductivity of the aquifer between the Surge Pond and the wells, the hydraulic connection between the Surge Pond and the groundwater system, and assigned aquifer storage. The model is capable of simulating a reasonable match in timing and magnitude of hydraulic responses in this area.

Observation wells near East Fork Armells Creek and Stocker Creek completed in alluvium show the model is capable of simulating a reasonable response to changing water levels in the creeks. To simulate a reasonable response to the changes in the creek water levels, the river conductance term was adjusted along with the low hydraulic conductivity assigned to Layer 2 below the creek. To adequately simulate the observed response, the low value of hydraulic conductivity assigned to the shallow alluvium of Layer 2 was removed from below the creek bed in the area of East Fork Armells Creek. This change in hydraulic conductivity in Layer 2 was carried over to both steady-state models.

Hydrographs showing the observed and simulated water level changes for wells in the vicinity of the Clearwell show that the model is capable of simulating the magnitude and timing of mounding that occurred in response to the liner tear.

The mean residual error for the long-term transient calibration was -0.53 and the absolute residual mean error was 1.80. **Table 4-7** presents the calibration statistics for the 87 target locations and 994 head targets. The transient simulation provided a good match to both the timing and magnitude of stresses, including the tear in the Old Clearwell liner. The relatively low absolute residual mean suggest this model is well calibrated to this large-scale long-term transient event.

Table 4-7. 2005-2007 Transient Model Statistics

Residual Mean (feet)	-0.53
Absolute Residual Mean	1.80
Residual Standard Deviation (feet)	2.24
Range of Observations (feet)	164.6
Standard Deviation/Range of Observations	0.014

Hydrographs in the area of the SOEP show variations in water levels that slightly mimic precipitation patterns. Initially, net recharge through the SOEP was set at 10 percent of measured precipitation for each stress period. The recharge rates were then adjusted within reason to better match well hydrograph response. The adjusted transient recharge rates are provided in **Appendix P**.

During the transient calibration, initially seasonal areal recharge rates for both background and clinker outcrops were estimated based on a percentage of monthly precipitation for a given stress period and input to the model. Initial calibration simulations indicated that variable areal recharge for background and clinker outcrops had little effect on water levels in wells. As a result, steady-state areal recharge rates were used in the transient calibration.

4.2.5 2014 Steady-State Calibration

A total of 57 pumping wells were simulated as actively pumping in the 2014 steady-state model. The pumping rates for these wells were established as the average pumping rate for August-October 2014, except where noted in **Section 2.6.6**. The exceptions are for wells where the measured rate was suspect, in which case previous average measured rates were used after adjusting for assumed measurement errors. **Table 2-13** and **Appendix J** show the pumping rates used in the 2014 model.

Recharge rates used in the 2014 steady-state model are presented on **Figure 4-26** which ranged from 7.07×10^{-6} to 1.38×10^{-3} feet/day. These rates, as applied over the respective areas, resulted in inflow that was within the range of estimated inflow for background recharge and pond seepage.

Appendix M contains calibration statistics resulting from the 2014 steady-state model based on 116 head targets. All head target statistics, groundwater exchange data, and the other general components of the water balance meet the steady-state model calibration goals. Further, visual comparison of the simulated and observed potentiometric maps show that, in general, groundwater flow directions and gradients were similar.

4.2.5.1 2014 Calibration to Head Data

The calculated residual mean for all target wells is 0.13 feet indicating that the overall model is not biased (Anderson et al., 2015). The absolute residual mean was 1.70 feet, which meets the calibration goals of less than 2 feet. The residual standard deviation divided by the range of observed elevations (160.92 feet) is 1.3 percent which is less than the calibration goal of less than 5 percent. The maximum residual is 4.84 feet and the minimum residual is -4.49 feet, which is within the calibration goal of ± 5 feet. **Figure 4-27** is a plot showing simulated vs. observed target values that are evenly distributed around a 1:1 line, demonstrating there is no groundwater elevation bias (Anderson et al, 2015) and that the model is well-calibrated.

Figure 4-28 through **Figure 4-34** are maps showing the simulated potentiometric surfaces for Layers 2 through 8, for the 2014 steady-state calibration. Comparison of the computed potentiometric contours to those based on field measurements (**Figure 2-12** through **Figure 2-14**) indicates a good match between simulated and observed heads and gradients. Slight variations exist between the observed and simulated potentiometric surfaces. For example, similar to the 2005 Steady-State calibration, observed and simulated shallow potentiometric surfaces vary slightly in flow direction and gradient in the west central portion of the model. However, due to the sparse number of observed

groundwater elevations in this area, the observed flow directions and gradients are somewhat uncertain. Simulated groundwater elevation contours for Layer 5 and Layer 7 match relatively well to the observed potentiometric surface as shown in **Figures 2-13 and 2-14**, respectively.

Residuals at each target location are shown on **Figure 4-28** through **Figure 4-34**, with positive (blue) values indicating the simulated head was less than the observed head and negative (red) values indicating the simulated head was greater than the measured value. The residuals posted on these figures allow for a spatial analysis of the calibration.

The 2014 steady-state model shows a relatively even distribution of positive and negative residuals with the exception of near East Fork Armells Creek in Layer 4 where the model under-predicts heads (**Figure 4-30**). These heads are largely controlled by the assigned elevation of the creek. The under-predicted heads may be related to uncertainty in interpolated elevations in the creek used to assign River Package cell stages as described in **Section 3.4.3**.

Table 4-8 indicates that model layers exhibit some spatial bias. Based on mean residuals, Layers 2, 3 and 7 have slightly over-estimated groundwater elevations, while in Layers 4 through 6 and 8, they are slightly underestimated.

Table 4-8. 2014 Calibration Statistics by Layer

Layer	Absolute Residual Mean	Residual Mean
Layer 2	1.51	-1.28
Layer 3	1.71	-0.59
Layer 4	1.65	0.01
Layer 5	2.02	0.76
Layer 6	1.48	1.02
Layer 7	0.89	-0.51
Layer 8*	2.35	2.35

* Layer only has two targets

4.2.5.2 2014 Calibration to Flux Data

The components of the 2014 steady-state water balance were compared to the components of the estimated water budget to ensure the model simulation incorporated the appropriate rates of flux. **Table 4-9** presents the estimated water balance along with the corresponding simulated water balance. The estimated water balance was also presented in **Table 2-4** and the basis for the estimates discussed in **Section 2.6**. All the simulated flux values fall within the estimated ranges with the exception of discharge to Stocker Creek which is slightly under predicted but close to the calculated minimum. **Appendix O** contains the groundwater model water balance resulting from the calibrated 2014 steady-state model.

Table 4-9. Summary of Estimated and Simulated Water Balance for 2014

	2014						Simulated Groundwater Balance	
	Min (ft^3/d)	Max (ft^3/d)	Estimate (ft^3/d)	Min (gpm)	Max (gpm)	Estimate (gpm)	Simulated (ft^3/d)	Simulated (gpm)
Inflows								
Underflow In	1,566	4,039,233	73,362	8	20,982	381	52,416	273
Surge Pond Seepage	5,103	51,031	16,137	27	265	84	12,953	67
Infiltrating Background Recharge	9,398	15,663	12,531	49	81	65	12,466	65
Infiltrating Clinker Recharge	1,118	7,825	4,471	6	41	23	2,166	11
SOEP Infiltrating Recharge	2,749	4,582	3,666	14	24	19	2,784	14
STEP Pond Seepage	2,135	4,434	3,284	11	23	17	4,276	22
Total IN	**22,069**	**4,122,768**	**113,451**	**115**	**21,415**	**589**	**87,060**	**453**
Outflows								
Underflow Out	664	400,356	57,535	3	2,080	299	51,208	266
Discharge to East Fork Armells Creek	2,588	12,213	7,401	13	63	38	10,,897	57
Discharge to Stocker Creek	295	2,951	1,623	2	15	8	219	1
Groundwater Extraction	16,675	33,351	25,013	87	173	130	24,649	128
Total OUT	**20,855**	**450,138**	**92,522**	**108**	**2,338**	**481**	**86,973**	**452**

Notes: ft^3/d = cubic feet per day; gpm = gallons per minute

Table 4-10 presents the simulated flux from groundwater to East Fork Armells Creek. The overall simulated pattern of groundwater interaction with East Fork Armells Creek was similar to observed gaining and losing patterns with the exception of Reach 4. The model predicted this reach to be a losing reach, while surface water flow measurements made in October 2014 indicated this was a gaining reach. Between Reach 1 and 2, the model accurately predicts losses in creek flow; however the magnitude of the losses predicted by the model is less than observed values. Initial construction and interpolation of river cell elevations in Reach 1 created a gaining river reach (a net gain in flow within the reach). Because synoptic streamflow measurement data typically revealed a net loss in flow through this reach, the interpolated river cell elevations were adjusted by flattening the downstream gradient to create more of a losing condition where water flows from the creek to the groundwater.

The model also simulates the observed overall net gain through Reaches 3 through 6. Flow measurements indicate a gain in Reach 4; however, the model simulated an overall loss in flow through Reach 4. Although the model does not entirely match overall measured net losses and gains through each individual Reach, the simulated flow directions and flux is reasonable and stream flow measured gains and losses are relatively small and likely difficult to measure in an open channel with great accuracy. Based on historical statistics of synoptic measurements, the simulated flux from groundwater to East Fork Armells Creek within each Reach is within the historical range of measurements. Hydrometrics (Personal Communication, 2015b) noted several flow values measured at the flumes may be inaccurate

Table 4-10. 2014 Measured and Model Simulated Flow Into and Out of East Fork Armells Creek

Model Reach	Station No. to Station No.	Oct. 2014 Flow to East Fork Armells Creek from Groundwater. (GPM)	Simulated Flow to East Fork Armells Creek from Groundwater. (GPM)
0	(Model Boundary to AR-1)	N/A	45
1	(AR-1 to AR-9)	-785	-19
2	(AR-9 to AR-8)	-107	-24
3	(AR-8 to AR-7)	43	43
4	(AR-7 to AR-6)	60	-5
5	(AR-6 to AR-11)	17	19
6	(AR-11 to AR-10)	44	7
7	(AR-10 to Model Boundary)	N/A	-10

Note: Negative values indicate a loss in streamflow

As discussed in **Section 2.6.6**, it was necessary to reduce pumping rates in several wells (987D, 906D, 984D, 905D, 911D, 380D, 968D, 960D, and 961D) beneath the STEP Main Dam to calibrate to head targets in this area in the 2014 steady-state calibration. Hydraulic conductivity values that would have been necessary to calibrate the model using the higher pumping rates are outside of reasonable ranges for bedrock.

4.3 CALIBRATION RESULTS SUMMARY

The SOEP and STEP groundwater model is well-calibrated and has been calibrated to several independent steady-state and transient data sets. Calibration statistics and good visual qualitative matches for the calibration data sets suggest this model is robust and adaptable to changing hydraulic conditions around the SOEP and STEP. Based on the results presented in this section, the numerical model is an appropriate tool to conduct predictive evaluations of groundwater flow.

5.0 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to quantify uncertainty in the calibrated model relative to uncertainty in model inputs. This type of analysis helps identify input parameters to which the numerical model is most sensitive and to verify the selection of parameters applied to the model to provide the best match to observed groundwater elevations. Methods used to complete the sensitivity analysis, along with the results, are described below. Additional sensitivity analyses of the model predictions regarding groundwater capture are described in **Section 6.3**.

The sensitivity analysis was conducted using the 2014 steady-state simulation by varying selected model input values within plausible ranges to document the effect on model calibration statistics. **Table 5-1** lists model input parameters tested in the sensitivity analysis. Parameters that appeared to have the greatest effect on residual statistics during manual and automated calibration based on changes in in residual statistics following parameter adjustments were selected for analysis, including:

- Horizontal and vertical hydraulic conductivity;
- Net recharge rates;
- Pond seepage rates;
- Conductance of River Package cells simulating East Fork Armells Creek; and
- Capture well pumping rates.

The sensitivity analysis was completed using Groundwater Vistas Auto-Sensitivity function for most parameters. Analysis of capture well pumping rates was not completed using the Auto-Sensitivity function as the pumping rates were adjusted outside the function to a lesser degree than the other parameters.

The following is a summary of the ranges of values tested for the different types of input parameters in the sensitivity analysis:

- Horizontal and vertical hydraulic conductivity values were multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- Net recharge rates were multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- Pond seepage rates were multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- River bed conductance was multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- Simulated capture wells pumping rates were multiplied by 0.75 and 1.25.

The uncertainty of most parameters is estimated to be up to an order of magnitude and therefore parameters were multiplied within by factors a range of 0.1 to 10 times. The uncertainty associated with pumping rates is estimated to be ± 25% so pumping rates were multiplied by factors of 0.75 and 1.25.

Table 5-1. Parameters Altered in the Sensitivity Analysis

Horizontal and Vertical Hydraulic Conductivity	
Zone	**Description**
Zone 1	Siltstone/Claystone
Zone 2	Siltstone/Claystone
Zone 3	Interbedded Siltstone/Sandstone
Zone 6	Siltstone/Claystone
Zone 10	Interbedded Siltstone/Sandstone
Zone 12	Interbedded Siltstone/Sandstone
Zone 15	Alluvium
Zone 21	Siltstone/Claystone
Zone 33	Interbedded Siltstone/Sandstone
Zone 34	Alluvium/Colluvium
Zone 49	Alluvium
Zone 57	Sandstone
Zone 60	Interbedded Siltstone/Sandstone
Zone 86	Sandstone
Zone 87	Interbedded Siltstone/Sandstone
Zone 96	Fine Grained Alluvium
Pumping	
Well	**Description**
All	Wells were adjusted as a group

Recharge	
Zone	**Description**
Zone 1	Recharge Background
Zone 5	Recharge Clinker Exposures
Pond Seepage	
Zone	**Description**
Zone 2	Cell E North
Zone 3	Cell A North Extension
Zone 4	Old Clearwell
Zone 6	SOEP
Zone 7	Cell A
Zone 8	Cell B
Zone 10	Cell E South
Zone 13	Edge of Clearwell
Zone 15	Cell D
Riverbed Conductance	
Reach	**Description**
Reach 0	Southwest model boundary to gaging station AR-1
Reach 1	Station AR-1 to AR-9
Reach 2	Station AR-9 to AR-8
Reach 3	Station AR-8 to AR-7
Reach 4	Station AR-7 to AR-6
Reach 5	Station AR-6 to AR-11
Reach 6	Station AR-11 to AR-10
Reach7	Station AR-10 to the northern model boundary
Reach 10	Stocker Creek

Figure 5-1 through **Figure 5-6** summarize results of the sensitivity analysis. These figures show the absolute residual mean for each sensitivity run as well as for the calibrated model. The relationships are important indicators of parameter sensitivity. Parameters that the model is most sensitive to show the greatest change in the absolute residual mean, while those that are least sensitive show little change in the absolute residual mean.

Results of the sensitivity analyses indicate the model calibration is most sensitive to increases in horizontal hydraulic conductivity, and pond seepage. The results also indicate that the model is sensitive to large increases in background recharge, but increases of this magnitude do not seem plausible based on the conceptual model. The sensitivity analysis also shows that model calibration would not be improved by changes in any of the parameters evaluated. Details of the sensitivity analyses for these parameters (and others determined to be less sensitive) are discussed further below.

5.1 Hydraulic Conductivity

A sensitivity analysis was completed on 16 model hydraulic conductivity zones. Horizontal and vertical hydraulic conductivity values in zones selected for analysis included those that comprise a relatively large portion of the model domain, or were observed to greatly influence model calibration (based on

changes in residual statistics following adjustment in values for those zones). Both horizontal and vertical hydraulic conductivity values within the 16 model zones were evaluated resulting in 32 analyses of sensitivity. Seven multipliers were applied for each analysis; results are shown on **Figure 5-1** (horizontal hydraulic conductivity) and **Figure 5-2** (vertical hydraulic conductivity). The model zones referred in this discussion are shown on **Figure 4-1** through **Figure 4-7** (model Layers 2 through 8).

The results show the model is more sensitive to increases and decreases in horizontal conductivity than to vertical hydraulic conductivity, and that there are two zones that the model is most sensitive to. The two zones that show the most rapid increase in the absolute residual mean when the calibrated model value is altered are:

- Zone 12: For both increases and decreases horizontal hydraulic conductivity. Zone 12 represents Sub-McKay interbedded siltstone and sandstone which cover widespread portions of Layers 2, 3, and 4, and small portions of Layer 5 southwest of the SOEP (**Figure 4-1** through **Figure 4-4**); and
- Zone 49: For decreases in horizontal hydraulic conductivity. Zone 49 represents alluvium in Layers 2, 3, and 4 (**Figure 4-1** through **Figures 4-3**).

Order-of-magnitude changes of Zone 12 and Zone 49 horizontal hydraulic conductivity result in an absolute residual mean greater than 3 feet. The model is much less sensitive to smaller (doubling or halving) changes in hydraulic conductivity for Zone 49, but for Zone 12 these lesser changes result in an absolute residual mean of about 2 feet. It should be noted that although the model is sensitive to these two zones, the result of any change that was evaluated provides a poorer calibration than for the calibrated model values.

The model is also sensitive to both changes in horizontal and vertical hydraulic conductivity within a number of zones other than Zone 12 and Zone 49, although to a more moderate degree. Order of magnitude changes in many of these other zones result in an absolute residual mean greater than 2 feet and less than 3 feet, but the model is less sensitive to smaller changes in these zones. It is not believed that hydraulic conductivity could vary in these zones by an order of magnitude from the calibrated model values, and changes of that magnitude drastically worsen the calibration.

The calibrated model hydraulic conductivity values (multiplier of one in the sensitivity analysis) provided the smallest absolute residual mean for 22 of the 32 horizontal and vertical hydraulic conductivity analyses completed. Changes in several vertical hydraulic conductivity zones (Zones 1, 3, 6, 10, 12, 15, and 86) and three horizontal hydraulic conductivity zones (Zones 6, 10, and 15) resulted in an absolute residual mean slightly lower than the calibrated model value of 1.70 feet. However, the values with an improved mean were not incorporated in the calibrated model because the improvement in the absolute residual mean for these four zones was so small (1.64 to 1.69 feet), and the changes resulted in less favorable calibration (an increased absolute residual mean) in the 2005 steady-state model.

5.2 BACKGROUND AND CLINKER RECHARGE

A sensitivity analysis was completed on the two model recharge zones that represent Background (Zone 1) and Clinker (Zone 5) outcrop recharge. Seven multipliers were used for each analysis for these parameters and results are shown on **Figure 5-3**.

The results indicate that the model is more sensitive to increases in the recharge for these two zones than for decreases. Increases of 5 to 10 times the base recharge rate results in an absolute residual mean greater than 2.89 feet and as high as 11.16 feet. In contrast, decreases of 0.1 to 0.8 times the base recharge rate results in less of an increase in the mean, ranging from 1.70 to 2.36 feet.

It is plausible that net recharge values could be as much as an order of magnitude higher, but the likelihood of this condition is difficult to assess. The model's ability to transmit additional recharge is limited as evidenced by the fact that increases in recharge result in a less favorable and higher absolute residual mean. The parameters of horizontal and vertical hydraulic conductivity would need to be increased to improve the model's ability to transmit additional recharge.

The analysis of both recharge zones resulted in the absolute residual mean being the lowest for a multiplier of one. This suggests the calibrated model recharge rates for these zones already incorporated into the model provide the best calibration statistics.

5.3 POND SEEPAGE

A sensitivity analysis was completed on recharge zones representing seepage from the SOEP and STEP. Seven multipliers were used for each analysis and the results are shown on **Figure 5-4**.

Results of the pond seepage sensitivity analysis indicate that the model is most sensitive to increases in seepage from model recharge in the following zones:

- Zone 6 –SOEP area, and
- Zone 7 – Cell A.

Increases of 5 to 10 times the base recharge rate for these two zones results in an absolute residual mean of nearly 3 feet to as high as 11.94 feet. In contrast, decreases of 0.1 to 0.8 times the base recharge rate results in less of an increase in the mean, resulting in a maximum value from 1.70 to 2.83 feet.

The model is also sensitive to seepage increases for certain other zones (other than Zone 6 and Zone 7), although to a lesser degree. These other zones to which the model is sensitive include the following:

- Zone 10 – South area of Cell E, and
- Zone 2– North area of Cell E.

Order of magnitude increases in these zones result in an absolute residual mean ranging from 4.77 feet to 5.03 feet. The model is much less sensitive to decreases in recharge for these two zones, where order of magnitude reductions result in mean values of 1.84 to 1.90 feet.

The model also shows minor improvements in head matching statistics with increases of 2 and 5 times the recharge applied in Zone 4 (Old Clearwell). However, the improvement on the calibrated mean of 1.70 feet is very slight (1.68 feet) and increases in pond seepage rates as much as 2 times the current simulated rates in Zone 4 would result in seepage rates higher than estimated as part of the conceptual model. The decreases noted result in a poorer calibration for the 2005 Steady-State model.

The sensitivity analysis of pond seepage zones suggests the calibrated model recharge rates for these zones already incorporated into the model provide the best calibration.

5.4 RIVERBED CONDUCTANCE

The sensitivity of the model to riverbed conductance was evaluated by adjusting the conductance term in 9 reaches of the model River Package cells that represent East Fork Armells Creek and Stocker Creek. Seven multipliers were used for each analysis and the results are shown on **Figure 5-5**.

The sensitivity results plot shows that the model calibration is not sensitive to increases or decreases in riverbed conductance, with a maximum absolute residual mean of 1.70 resulting from the analysis, the same as the calibrated value.

5.5 PUMPING

A sensitivity analysis was completed on model pumping rates by applying rates of 0.75 and 1.25 times the calibrated model specified rates. Results of the pumping rate sensitivity analysis are shown on **Figure 5-6**.

The sensitivity results plot shows that the model is more sensitive to an increase in pumping rates, which raises the absolute residual mean to 2.41 feet, than it is to a decrease in rates which results in a mean of 2.05 feet. The calibrated model specified rates (multiplier of 1) provide the lowest absolute residual mean.

5.6 SUMMARY OF SENSITIVITY ANALYSIS RESULTS

Results of the sensitivity analysis show that the model is most sensitive to the following:

- Increases and decreases in horizontal hydraulic conductivity for Zone 12 - Shallow, Mid-, and Deep Sub-McKay Interbedded Siltstone and Sandstone in Layers 2, 3, 4 and 5;
- Decreases in horizontal hydraulic conductivity for Zone 49 – Alluvium in Layers 2, 3, and 4;
- Increases in Background and Clinker area recharge; and
- Increases in pond seepage at SOEP and Cell A.

Of these four parameters the model is most sensitive to changes in recharge and pond seepage, where order of magnitude changes result in absolute residual means of up to 11.94 feet, than to hydraulic conductivity (maximum mean value of 3.88 feet). The sensitivity to recharge and pond seepage is not surprising, given the large area of the model covered by the background and clinker recharge zones, and by the fact that a majority of the target head data points lie in close proximity to the ponds.

Calibrated model values for the parameters to which the model is most sensitive to are based on the data and calculations described in **Section 2.0**. For these parameters, the degree of uncertainty is relatively small, meaning that even though the model is sensitive to these values, they are reasonably well defined.

The model is least sensitive to riverbed conductance, which shows almost no change in the absolute residual mean over the range of plus or minus an order of magnitude. Although there is a large degree of uncertainty with this parameter due to an absence of field data, the sensitivity analysis shows that the uncertainty has little impact on model head-matching results.

For the majority of the parameters, zones, and reaches evaluated (53 total analyses completed), the absolute residual mean is lowest for the calibrated model specified values (a multiplier of 1 in the sensitivity plots). Twelve of the hydraulic conductivity zones, and one of the pond seepage zones show a slightly better absolute residual mean for values different from those specified in the calibrated model. The improvement in the mean, however, is very small, and the necessary changes to hydraulic conductivity do not improve calibration for the 2005 Steady-state model, and changes to the pond seepage parameters would put them outside of the estimated range. Therefore the sensitivity analysis shows that the parameter specifications for the calibrated model are appropriate for evaluating site conditions and for particle tracking described in the next section.

6.0 PARTICLE TRACKING AND CAPTURE ANALYSIS

Following calibration and sensitivity analyses, the numerical model was used to perform particle tracking to assess the effectiveness of the current groundwater capture system with respect to BSLs. This analysis should be considered an approximation and additional lines of evidence, such as field measurements of pumping drawdown and trends in water quality, should also be consulted in a weight-of-evidence approach. It should be noted that actual cleanup values for some parameters may be greater than BSLs. Hence the analysis presented herein is conservative.

Particle tracking simulates advective transport of dissolved constituents in groundwater. Advection is the transport of a solute by the bulk movement of groundwater; the movement of particles within flowing water at the average linear groundwater velocity. Particle tracking does not take into account other hydrodynamic processes that can affect the movement of solutes in groundwater including diffusion, dispersion, retardation (adsorption), or decay (chemical reactions).

This section presents the set up and result of forward particle tracking performed to analyze capture system effectiveness as well as reverse particle tracking used to evaluate the source of elevated indicator parameter concentrations in an area south of the SOEP and west of the Surge Pond.

6.1 CAPTURE ANALYSIS SET UP

MODPATH (Pollack, 1994) was used to complete particle tracking simulations to assess the effectiveness of the current groundwater capture system. The program was used to calculate particle pathlines based on advective flow. With the exception of capture rates, hydraulic properties and boundary conditions from the 2014 steady-state calibration were used for the particle tracking analysis.

Representative capture rates used for the particle track analysis are listed in **Table 6-1** and were selected following review of the last several years of capture system data in order to properly simulate long-term groundwater movement and capture. Review of average annual pumping rates for each well from 2006 through 2015 indicates that 2014 average annual pumping rates are generally representative of current groundwater capture system operation with a few exceptions. Average 2014 pumping rates for 10 wells were not representative of long-term rates. Estimated long-term rates for these wells were based on other data:

- Average annual 2014 pumping rates for wells 987D, 906D, 984D, 905D, 911D, 380D, 968D, 960D, and 961D were not used. As previously noted (see **Section 3.4.5**) these wells had anomalously high measured pumping rates for 2014. Instead, pumping rates for these wells are the average pumping rate for the period of January 2009 through December 2011; and
- The pumping rate for well 2024D was adjusted to equal the 2015 average annual pumping rate. Well work was being conducted in 2014 and pumping at the well was intermittent. From the end of 2014 through November 2015 the well pumped consistently between 7 and 9 gpm.

Head output from a steady-state simulation using the capture rates listed in **Table 6-1** were used to generate velocity inputs for MODPATH.

Table 6-1. Extraction Rates used in Capture Analysis

Well	Estimated Pumping Rate (gpm)	Well	Estimated Pumping Rate (gpm)
2000D	6.3	934D	0.69
2003D	6.23	938A	-----
2008D	2.53	940A	-----
2013A	16.72	943A	6.89
2016A	1.89	944A	3.44
2019D	2.95	945A	8.58
2021D	1.98	958D	1.28
2024D	3.01[b]	960D	2.46[a]
369D	0.0001	961D	1.32[a]
375D	1.5	962D	5.03
376D	0.002	963D	4.9
377A	1.3	966A	3.81
378A	2.2	968D	0.94[a]
379D	0.06	969D	2.22
380D	1.03[a]	970D	0.02
382A	3.35	976D	0.68
383D	0.29	984D	1.14[a]
393D	0.35	985A	0.1
905D	1.69[a]	987D	1.85[a]
906D	2.29[a]	988D	1.25
910A	0.0004	989D	1.29
911D	1.13[a]	991A	0.16
913A	0.0004	993D	0.32
916A	14.4	994A	1.84
922A	4.62	997A	2.02
924A	0.02	998A	2.23
927D	1.21	EAP-119	0.28
928D	4.87	EAP-205	2.05
932D	5.32	EAP-208	0.42
933D	0.09	PW-704D2	7.02

a 75% of rates from January 2009 through December 2011
b Calculated as 75% of rates from January 2015 through November 2015.

Effective porosity values were assigned to model cells in order to generate velocity inputs for MODPATH. Effective porosity values for different lithologies are within range of literature reported values presented in **Table 3-1.** Assigned effective porosity values are summarized in **Table 6-2** below.

Table 6-2. Assigned Values of Effective Porosity

Unit	Effective Porosity (unitless)
Alluvium	0.24
Bedrock	0.1
McKay Coal	0.09

In order to help evaluate capture system effectiveness, two different types of particle tracking analyses were executed. Analysis of water quality data suggests that there are some areas where groundwater is currently being affected by active sources of indicator parameters to groundwater. There are also other areas where groundwater exhibits concentrations of indicator parameters exceeding BSLs that appear to result from previous groundwater conditions where there may have been more pond seepage and flow directions and gradients were different. For this reason separate particle tracking simulations were run to represent groundwater coming from current sources, and groundwater from areas exceeding BSLs that appear to be residually impacted from previous pond configurations, but are not currently receiving process pond water. Active sources are thought to be seepage from the single-lined STEP cells (A, E, and Old Clearwell) and periodic deep percolation through the reclaimed SOEP.

Particles were input into active source areas and locations within areas exceeding BSLs outside of source areas based on the current extent of groundwater exceeding BSLS in each model layer as shown on **Figure 6-1** through **Figure 6-3**). It should be noted particles do not represent concentrations or dissolved mass of any constituent, but instead the particles illustrate flow paths from these areas.

Six particle tracking simulations were completed. The first simulation included particles released within the footprint of Cell E, Cell A, and the SOEP to represent active source areas. The other five simulations included particles released in areas exceeding BSLs outside of source areas in each of model Layers 2 through 6. Particles were not released in Layers 7 through 8 because no wells in these layers currently exceed BSLs. In each simulation, particles were input into an area that encompassed the known extent of groundwater exceeding BSLs for each layer. These areas were delineated as follows:

- Source Areas – The extent of the source areas is defined by the first saturated layer below the footprint of Cell E, Cell A, and the SOEP area, which included cells in Layers 2, 3, 4, 5, and 6. The extent of the source areas is shown on **Figure 6-1** through **Figure 6-3**.
- Layer 2 – The extent in this layer (**Figure 6-1**) was delineated using all the plume maps for wells completed in the shallow Layers 2 and 3. Particles were not placed in dry cells.
- Layer 3 – The extent in this layer (**Figure 6-1**) was delineated using all the plume maps for wells completed in Layers 3. Particles were not placed in dry cells.
- Layer 4 – The extent presented in this layer (**Figure 6-2**) was delineated using all the plume maps for alluvium (**Figure 2-25** through **Figure 2-28**) and any BSL exceedance in a well completed in Layer 4.
- Layer 5 – The extent in this layer (**Figure 6-3**) was delineated using any BSL exceedance in a well completed in Layer 5.

- Layer 6 – The extent in this layer (**Figure 6-3**) was delineated using any BSL exceedance in wells completed in Layer 6.
- A few isolated wells (366S, 374S, 926S, 977A, and 979S) exceeded the BSL for dissolved boron, specific conductance, and/or sulfate. The source of elevated concentrations of these parameters is evaluated in a separate particle tracking analysis discussed in **Section 6.2.2**.

Particles were placed within the boundaries and spaced on approximately 200-foot centers. Particles starting locations released within the source areas were set to the bottom of the cell in Layer 2 and the top of the cell for particles released in Layer 3 and 4. Particle starting locations released within areas exceeding BSLs outside of source areas were set to the vertical center of the model cell except in Layers 2 and 6. The vertical starting location for particles released in Layer 2 was set to the cell bottom to ensure the particle was placed in the saturated part of the cell. The vertical starting location for particles released in Layer 6 was set at the top of the cell. Forward particle tracking for each simulation was then completed, and the particles were moved through the steady-state flow field over 50-year period.

6.2 CAPTURE ANALYSIS RESULTS

Figure 6-4 through **Figure 6-9** present animated particle tracks (paper copies of this report contain static images) for particles started in the active source area and in model Layers 2 through 6 outside of active plume areas as they move through the 50-year simulation. As the particles move into other layers they are symbolized with a different color. The first 10 years of the simulation are portrayed slower than the last 40 years to better illustrate the capture of particles in the alluvial system.

6.2.1 Source Areas

Figure 6-4 shows results of particle tracking for particles released in source areas. These results are discussed below. Most of the particles released in the SOEP started in Layer 2 and 3. A small area in the southern portion of the SOEP started in Layer 4.

Particles released beneath the SOEP in Layers 2 and 3 near the native alluvium beneath the fly ash generally converge on the alluvium in Layer 3 and get captured by well 966A or travel toward the SOEP dam where they move downward into Layer 4 beneath the dam. Most of these particles then move into the alluvium beneath the STEP area, and some are not captured within 50 years according to the simulations, but might be captured with continued capture system operation. Particles released beneath north and west portions of the SOEP area generally travel north; some of these are captured by wells, and some remain uncaptured. Particles released in the south and east portions of the SOEP travel northeast past the SOEP dam toward the STEP area, some of which then travel into the alluvium beneath the STEP area, continue traveling in Layer 4, or flow down into Layer 5.

Some particles are released in Layer 4 beneath the southern portion SOEP. These particles travel northeast in Layer 4. Some of these particles remain beneath the footprint of the SOEP after 50 years, some travel beneath the SOEP dam, then return to Layer 3 and enter the alluvial channel beneath the STEP, and some travel downward into Layer 5 and travel north, and some are not captured within 50 years according to the simulations, but might be captured with continued capture system operation.

Particles were released in Layer 2, 3 and 4 beneath the STEP source areas (Cell A, Cell E, Old Clearwell). Most of the particles released beneath the STEP converge on the alluvial channel and are captured by wells within 50 years either before or after traveling below the STEP Main Dam. Particles released below the north side of Cell E and the Old Clear well travel northeast and are ultimately captured below the STEP Main Dam. Particles released within Cell A converge on the alluvial channel beneath the STEP area with the exception of a few particles along the north edge of the cell that travel north and down into Layer 5 and are not captured.

6.2.2 Outside of Active Source Areas

Figures 6-5 through **6-9** show result of particles released in groundwater in areas exceeding BSLs that are outside of active source areas. These results are discussed below.

Particles Released in Layer 2

There are just a few saturated portions of Layer 2 in areas that exceed BSLs that are outside of source areas: east side of the SOEP; south side of Cell A; and East Fork Armells Creek alluvium. Particles that start near the SOEP and STEP area in Layer 2 (**Figure 6-5**) generally migrate to the northeast entering the alluvial channel beneath the STEP area where they travel down gradient and are captured below the STEP dam. A few other particles travel northeast and down into Layer 5 and do not make it to the alluvial channel below the STEP area in 50 years but are not captured.

Particles released in Layer 2 in the East Fork Armells Creek alluvium generally migrate downgradient until they terminate in River Package Cells representing East Fork Armells Creek or are captured by capture wells. No particles released within the delineated extent of groundwater exceeding BSLs make it past capture wells 943A, 944A, and 945A.

Particles Released in Layer 3

Particles released in Layer 3 (**Figure 6-6**) within areas that exceed BSLs beneath the SOEP outside of source areas generally travel to two different locations. Particles released just north of the SOEP source area travel north and down into Layer 4 away from the capture wells; particles released in the west, southwest, and southeast SOEP travel to the northeast and typically down into Layer 4. The majority of the particles that are released west of the SOEP initially travel vertically down into Layer 4 and then northeast and do not make it out of the footprint of the SOEP area by the end of 50 years; a few particles continue to travel northeast, where some travel to the alluvial channel beneath the STEP area. Particles starting in the southwest of this area are captured by well 966A. Similar to Layer 2, particles released in the southeast portion of the SOEP area generally migrate northeast entering the alluvial channel beneath the STEP area where they travel down gradient and are captured below the STEP dam. A few other particles travel northeast and down into Layer 5 and do not make it to the alluvial channel below the STEP area in 50 years and remain uncaptured.

Particles released in Layer 3 in the STEP area within areas that exceed BSLs outside of source areas generally converge on the alluvial channel beneath the STEP then they travel to the northeast and are captured by wells either before or after they travel beneath the STEP Main Dam. Particles released in Layer 3 below Cell D are captured by well 2019D. Particles initiated in Layer 3 to the north of Cell A flow to the north and northeast and are uncaptured.

Particles released in Layer 3 in the area between the STEP Main Dam and East Fork Armells Creek alluvium do not travel outside this area and are captured by wells.

Particles released in Layer 3 in the East Fork Armells Creek alluvium generally migrate downgradient until they terminate in River Package Cells representing East Fork Armells Creek or are captured by capture wells. Particles released within the extent of groundwater exceeding BSLs do not make it past capture wells 943A, 944A, and 945A.

Particles Released in Layer 4

Particles released in Sub-McKay bedrock in Layer 4 (**Figure 6-7**) area within areas that exceed BSLs outside of source areas near the SOEP typically follow a similar path as the particles released in these areas in Layer 3, with some exceptions. Particles released north of the SOEP travel north and down into Layer 5 where some are captured by well 2024D and others that enter Layer 5 continue traveling to the north and northwest and are not captured. In addition, a few particles that start west of the SOEP enter Layer 5 when they travel below the SOEP dam. Once the particles are in Layer 5 they travel northwest toward well 2024D and are not captured. Also, several particles in the southeast area travel vertically down into Layer 5 and to the northeast, however, they do not travel very far after 50 years.

Particles released in the bedrock of Layer 4 in the STEP area within areas that exceed BSLs outside of source areas generally follow the same flow paths as the particles released in Layer 3, migrating to the alluvial channel beneath the STEP and travelling northeast where they are captured by wells before or after they travel beyond the STEP Main Dam. The majority of particles in the STEP area released in Layer 4 beneath Cell D are captured by well 2019D. Particles initiated in Layer 4 on the north and west side and beneath Cell B and to the north and west of Cell A flow to the north and northeast and are not captured. Particles that enter Layer 5 and flow to the northeast are eventually captured by the wells below the STEP Main Dam.

Particles released in Layer 4 in the area between the STEP Main Dam and East Fork Armells Creek Alluvium are all captured by wells and do not travel outside this area.

Particles released in Layer 4 in the East Fork Armells Creek alluvium generally migrate downgradient until they terminate in River Package Cells representing East Fork Armells Creek or are captured by capture wells. No particles released within the extent of groundwater exceeding BSLS make it past capture wells 943A, 944A, and 945A.

Particles Released in Layer 5

Particles released in Layer 5 (**Figure 6-8**) in the STEP area within areas that exceed BSLs outside of source areas generally migrate to the north, northwest, and northeast. Particles released in an area to the west and northwest of Cell A are captured by well 2024D. Particles released on the southeast side of Cell A migrate north and east under Cell E and Cell D and are not captured in 50 years.

Particles released in Layer 5 in the area between the STEP Main Dam and East Fork Armells Creek Alluvium are all captured by wells with the exception of an area of particles below the north half of the dam that begin in low permeable material and do not migrate very far in 50 years.

Particles Released in Layer 6

Particles released in Layer 6 (**Figure 6-9**) in the STEP area beneath Cell B migrate to the northeast; one particle migrates to the south and is captured by well 958D.

Particles released in Layer 6 in the area between the STEP Main Dam and East Fork Armells Creek Alluvium are captured by wells with the exception of an area of particles in the north and east of the delineated area that exceeds BSL's. Some of the uncaptured particles migrate a very short distance in 50 years due to the low permeability assigned to the bedrock and some of the uncaptured particles flow to the north.

6.2.3 Captured and Uncaptured Particles

A 50-year particle track simulation was used to perform an endpoint analysis of particles released in groundwater exceeding BSLs in Layers 2 through 6. The purpose of the endpoint analysis was to identify areas where complete capture may not be occurring.

Source Areas

One important finding of particle tracking analysis is that no particles released from beneath the SOEP and STEP source areas travel past the capture wells below the STEP Main Dam and into East Fork Armells Creek within a 50-year period. **Figure 6-10** shows the starting points of particles released in source areas that were not captured within 50 years. All of the uncaptured particles from this analysis end up in low permeability areas with very slow groundwater velocities beneath the SOEP and STEP within 50 years. These uncaptured areas are summarized as follows:

- Particles originating beneath the north and northwestern portion of the SOEP source area. These particles migrate very slowly to the north;
- Particles released beneath the southwest area of the SOEP source area. These particles migrate very slowly northeast under the SOEP Dam;
- Particles originating in the southern portion of the SOEP source. Particles originating in this area travel slowly to the northeast.
- Particles released in a small area of Layer 2 beneath the SOEP Dam. These particles remain within the SOEP Dam after 50 years due to the relatively low permeability of the dam material;
- Particles originating along the northern edge of Cell A (these particles represent residual impact and not seepage from Cell A. These migrate slowly north; and
- Particles originating in the northwest corner of Cell E. These particles travel very slowly northeast and east.

Areas Outside Source Areas

Figures 6-11 through **6-15** show starting locations of particles released within areas exceeding BSLs outside of source areas near the SOEP and STEP areas in Layers 2 through 6, respectively, that are not captured within 50 years. The starting locations of these uncaptured particles are summarized as follows:

- A few particles released in an area east of the SOEP in Layers 2, 3, and 4. These particles travel very slowly northeast and end up under Cell E, the Old Clearwell, or Cell D after 50 years;
- Particles originating along the north and northwest margin of the SOEP in Layers 3 and 4. These particles migrate north less than 2,500 feet within 50 years;
- An area of groundwater west of the SOEP source area is uncaptured. Groundwater in this area travels northeast under the SOEP Dam;
- Particles originating in Layer 4 north of the SOEP and Cell A and beneath Cell B. These particles travel less than 2000 feet north of the SOEP and STEP within 50 years; and
- Particles originating in an area north of Cell A (in Layer 5) and beneath Cell B (in Layer 5 and Layer 6). The uncaptured particles released north of Cell A migrate approximately 2,500 feet north and northwest within 50 years and the uncaptured particles released beneath Cell B migrate to the north and northeast and travel less than 600 feet within 50 years.

As discussed above, the capture analysis suggests that some particles released north of the SOEP and STEP are not captured. Previous modeling had suggested that particles released in similar areas were not captured. As a result, Talen installed several monitoring wells in this region in 2012 and 2013 for the purpose of further characterizing hydrogeology and evaluating potential need for additional capture wells. This includes wells 2022D, 2023D, 2024D, 2025D, 2026D, 2031D, 2032D, and 2033D. Well 2024D was subsequently converted to a capture well.

The model suggests that particles to the west and north end of the SOEP near wells 369D and 367D (**Figure 6-12** and **Figure 6-13**) that are predicted to be uncaptured travel north (**Figure 6-6** and **Figure 6-7**). However, groundwater in wells immediately north of there (354D 2025D, 2031D and 2026D) has not exceeded BSLs (**Figure 2-33** through **Figure 2-36**), indicating that groundwater quality in that area is not currently impacted by process ponds.

Uncaptured particles released north of the SOEP area near 929D, 2032D, 2024D and 2033D (**Figure 6-7** and **Figure 6-8**) are simulated to travel north toward well 355D. Capture well 2024D is simulated to capture much of the water in this area in Layer 5. Some of the particles in Layer 4 in this area remains uncaptured. Groundwater samples from well 355D (Layer 5) have not exceeded BSLs for indicator parameters, indicating that groundwater quality in that area is not currently impacted by process ponds.

Particles released in the area near wells 2023D and 2022D (**Figure 6-6** and **Figure 6-7**) travel north uncaptured in Layer 4 towards wells 398D, 399D, 901D and well 2009D, respectively. Groundwater samples from wells 398D, 399D, 901D do not currently exceed BSLs for indicator parameters; samples from 2009D have exceeded the sulfate BSL but no other BSLs (**Figure 2-36**).

East Fork Armells Creek Alluvium

As discussed above, particle tracking analysis indicates that all particles released beneath SOEP and STEP that travel east past the STEP Main Dam are captured and prevented from migrating to the East Fork Armells Creek alluvium and into the creek. However, there are several wells within the alluvium along East Fork Armells Creek that intercept groundwater with concentrations of indicator parameters exceeding BSLs. **Figure 2-25**, **Figure 2-27**, and **Figure 2-28** indicate that the dissolved boron, SC and sulfate plumes in East Fork Armells Creek alluvium are not connected to plumes beneath the drainage

downgradient of the STEP Main Dam. Only the chloride plume is continuous from the STEP Main Dam to area near capture wells 943A, 944A, and 945A. This suggests that groundwater exceeding BSLs remaining in East Fork Armells Creek Alluvium is either residual from before the implementation of the current capture system or originates from sources upstream (south) of the SOEP or STEP.

Figure 6-11 through **Figure 6-13** show the starting locations of uncaptured particles as released in East Fork Armells Creek alluvium in Layers 2 through 4, respectively. These figures show that particles released northwest of wells 938A and 939A and few small areas southeast of there, end at cells representing the creek. All other particles originating in East Fork Armells Creek alluvium are captured by wells. Comparison of **Figure 6-11** through **Figure 6-13** to **Figure 2-25** through **Figure 2-28** indicates that many of the areas where uncaptured particles originate in East Fork Armells Creek only exceed BSLs for chloride, and not for dissolved boron, SC or sulfate. It should also be noted no groundwater defined within the East Fork Armells Creek alluvium plume passes the farthest downgradient capture wells 943A, 944A, and 945A.

6.2.4 Summary of Capture Analysis

Particle tracking suggests that groundwater exceeding BSLs for indicator parameters originating from most known source areas in the SOEP and STEP area will be intercepted by the capture system and that groundwater in most of the areas exceeding the BSLs are contained. Capture analysis results also suggest that the current capture system may not be completely capturing groundwater originating from some areas within 50 years, including:

- Groundwater within the beneath the north and northwestern SOEP area;
- Groundwater along the southwest and south edges of the SOEP source area;
- Groundwater within the source area along the northern edge of Cell A and Cell E;
- Groundwater beneath Cell A along the western edge and under the Evaporation Pad;
- Groundwater in areas of BSL exceedance outside of the source area beneath Cell B;
- Areas of BSL exceedance outside of the source area in the area north and northwest of the SOEP area;
- Areas of BSL exceedance outside of the source area in the area south east of the SOEP source area;
- Areas of BSL exceedance outside of the source area in the area northwest of Cell A and the Evaporation Pad and southeast of Cell A; and
- Areas of BSL exceedance in East Fork Armells Creek alluvium northwest of well 938A and 939A and a few smaller areas to the southeast of those wells. Much of this area exceeds BSLs for chloride only and flows toward the creek.

This analysis was based on a steady-state simulation with representative capture rates. Short-term transient influences were not simulated. Seasonal effects, such as increase in the stream stage, changes in pond management, and changes in number or pumping rates of capture wells, may slightly alter simulated particle traces. Since travel times in most units are relatively long (months to years), a steady-state analysis should represent groundwater capture adequately. The one area where transient stresses

could have an important effect on predicted capture is in coarse-grained alluvium along East Fork Armells Creek, where velocities are faster and travel distance to the creek is shorter.

As noted above, particle tracking does not take into account processes of attenuation (dispersion, retardation, decay) and is not capable of quantifying mass or concentrations of solutes in the aquifer or mass of solutes removed by capture systems.

6.3 CAPTURE ANALYSIS UNCERTAINTY

Uncertainty associated with some model inputs lends uncertainty in model predictions such as the capture analysis described above. An uncertainty analysis was completed to evaluate how sensitive capture analysis results are to a set of input parameters that are anticipated to both have a relatively high degree of uncertainty and also have an impact on predicted capture results. Parameters evaluated were those judged to have the greatest effect on capture analysis results, including pumping rates and effective porosity.

6.3.1 Reduced Pumping Rates

As previously described, there is uncertainty associated with pumping rates in capture wells due to the difficulty in measuring flow rates at individual wells. Hydrometrics personnel indicate that scaling occurs within the plumbing associated with the systems and obtaining accurate flow measurements from the systems is difficult.

Model calibration and sensitivity analyses indicate that the model is sensitive to changes in capture rates of ± 25 percent. Therefore, one additional capture analysis was performed to help further evaluate the uncertainty described above as related to capture well pumping rates. Extraction rates used in the capture analysis were multiplied by 0.75. Particles were initiated at the same starting locations as described in **Section 6.1**. Forward particle tracking was then executed, and the particles were moved through the steady-state flow field.

Particle tracking results from the reduced pumping rate scenario were largely similar to those described in **Section 6.2** above. Starting locations for uncaptured particles from source areas and within areas exceeding BSLs outside of source areas in Layer 2 through 6 were assessed and results are shown on **Figure 6-16** through **Figure 6-21**. Each figure includes side by side images of the 75% pumping scenario results and the standard simulation results for ease of comparison. These figures show possible source areas that are not being captured for the reduced pumping rate simulations, which are very similar to the locations described for the original pumping rates. The uncaptured particles for the reduced pumping rate scenario can be summarized as follow:

- Areas of uncaptured groundwater originating within the source area in the SOEP and STEP area are the same;
- The areas of uncaptured groundwater originating in Layer 2 in East Fork Armells Creek Alluvium is slightly increased;
- Areas of uncaptured groundwater originating within the plume boundary in Layer 3 and 4 in the SOEP and STEP area is slightly increased;

- The areas of uncaptured particles originating in Layer 3 and 4 in East Fork Armells Creek alluvium is larger. Most of this increased area contains chloride concentrations exceeding the BSL only and does not exceed BSLs for dissolved boron, SC or sulfate. All particles originating from the SOEP and STEP areas above the East Fork Armells Creek that migrate east of the STEP Main Dam are captured before reaching East Fork Armells Creek alluvium, and no groundwater defined within the East Fork Armells Creek Alluvium plume passes the farthest downgradient capture wells (943A, 944A, and 945A);
- An area of uncaptured groundwater north of the SOEP in Layer 5 is slightly increased; and
- An area uncaptured groundwater beneath Cell B and below the STEP Main Dam in Layer 6 is increased.

The uncertainty in the capture analysis with regards to pumping rates suggest that, although there is uncertainty in the measured pumping rates at the SOEP and STEP area, altering this parameter does not dramatically alter the prediction of capture performance.

6.3.2 Effective Porosity

Time-of-travel predictions are sensitive to effective porosity because groundwater velocity is inversely proportional to effective porosity. Effective porosity is difficult to measure in the field, and site-specific data are not available. As discussed in **Section 3.0** and **4.0,** the model was populated with what are considered to be standard literature-derived values for effective porosity.

Since effective porosity does not alter the flow field direction in any way, a change in effective porosity would result in the same particles being captured or uncaptured as presented in **Section 6.2**. However, effective porosity does impact the time-of-travel. With this in mind, the model was populated with a sparse set of particles, starting at locations that fell within the areas of BSL exceedance (presented in **Section 6.1**). The sparse set of particles allowed for visualization of the travel time along the particle trace. This analysis was also completed for a reduced period of time (10 years). Two additional simulations were designed and executed: a "low" effective porosity simulation and a "high" effective porosity simulation. For these two simulations, effective porosity was set to low and high values respectively, according to the range in literature (**Table 3-1**). **Table 6-3** below presents the effective porosity assigned to the major porosity zones in the model for these two scenarios, along with the values assigned in the standard case (presented in **Section 6.2**).

Table 6-3. Effective Porosity Values Applied to Uncertainty Simulations

Material	Zone	Low Effective Porosity Scenario	Standard Effective Porosity	High Effective Porosity Scenario
Alluvium	2	0.2	0.24	0.35
Bedrock	1	0.01	0.1	0.4
Coal	5	0.008	0.09	0.094

Figure 6-22 presents the results of the effective porosity uncertainty analysis. The most notable difference between the scenarios is that, under the high-end effective porosity scenario, particles that originated in the SOEP and STEP areas had barely traveled and were still within STEP and SOEP areas after 10 years, whereas for the standard effective porosity scenario, the particles were beginning to

travel outside the STEP and SOEP areas. For the low effective porosity scenario, the uncaptured particles had traveled a significant distance outside the SOEP and STEP areas after 10 years.

6.4 EVALUATION OF SOURCE OF GROUNDWATER WEST OF SURGE POND

Groundwater west of the Surge Pond in some alluvial and shallow bedrock wells (366S, 374S, 926S, 977A, 978S, and 979S) contain concentrations of some constituents (dissolved boron, specific conductance, total dissolved solids and sulfate) exceeding BSLs. Hydraulic gradients in shallow bedrock and alluvium in this area are relatively flat (**Figure 2-12**). In addition, gradients and flow directions in this area fluctuate seasonally in response to changes in the stage of the Surge Pond. When the Surge Pond level is lowered, groundwater flow is generally towards the Surge Pond and hydraulic gradients increase in magnitude. When the Surge Pond is filled, groundwater flow next to Surge Pond is away from the pond and gradients are flatter. Flat gradients and seasonal fluctuations make it difficult to clearly determine the potential sources of elevated constituent concentrations in groundwater from these wells.

Reverse particle tracking was performed by conducting a 30-year transient simulation to evaluate the effect of seasonal fluctuations on groundwater flow and potential sources of elevated constituent concentrations in groundwater in the area (**Figure 6-23**). The inputs and boundary conditions for the 2014 steady-state model were used for the simulation. The Surge Pond elevations were adjusted bi-annually based on the average historical record for the last 10 years, the Surge Pond elevation was assigned a low elevation of 3281.22 for the months of March through October and a high elevation of 3285.25 for the months of November through February. The assigned stages represent the average high and low elevations for the period of record of 2005 through 2015.

The model was run for a period of 30 years. Particles were placed in a circle with a radius of 100 feet around each of the impacted wells and tracked backwards through the transient flow field. The ending particle locations from this particle tracking simulation were then used as initial particle locations for another reverse particle tracking simulation using the same model. This cycle of using ending particle locations as initial particle locations for subsequent particle tracking was repeated twice to provide a total of approximately 60 years of seasonal changes in groundwater gradients in this area.

The particles travel backwards in time to the south and west with particle travel eventually terminating at the model boundary adjacent to WECO Rosebud Mine Pit A (**Figure 6-23**). Particle traces near the Surge Pond exhibit seasonal fluctuations. Seasonal changes in particle track directions are most prevalent near the Surge Pond (near wells 366S and 926S) and less prevalent farther from the Surge Pond (near wells 374S, 978S, and 979S). Seasonal variability is less noticeable west of well 366S.

Based on the particle tracking results, the source of groundwater in most of these wells is located somewhere southwest of the wells between the wells and WECO Rosebud Mine Pit A. Results suggest that the SOEP is not the source of elevated concentrations of constituents in these wells.

7.0 MODEL ASSUMPTIONS AND LIMITATIONS

The current numerical model described herein is capable of adequately simulating groundwater flow within the area of interest under a variety of conditions within a reasonable range. Calibration of the model to a variety of different aquifer stress conditions, as described in **Section 4.0**, improves confidence in the results and serves to address the inherent assumptions and limitations with models, discussed below.

As a result, the model is capable of assessing the effects of changes in water management practices at the SOEP and STEP on groundwater flow and advective transport. It should be noted that because particle tracking (an advective transport analysis) does not take into account processes of attenuation (dispersion, retardation, and decay), it is not capable of quantifying the mass or concentrations of various solutes residing in the aquifer or the mass of solutes removed by capture systems.

Groundwater models are mathematical representations of groundwater systems and, therefore, are guided by certain assumptions and limitations. Those that pertain to MODFLOW include:

- Saturated-flow conditions exist throughout the model domain;
- Darcy's Law applies;
- The density of groundwater is constant; and
- The principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system; aquifer heterogeneity and anisotropy can be adequately represented with an appropriate choice of aquifer properties and grid spacing.

The model is also governed by other important assumptions:

- Specific equipotential contour lines used to assign GHBs and no-flow boundaries provide an accurate and reasonable representation of the flow field at the model boundaries;
- Steady-state boundary conditions, based on average pumping and recharge rates, result in representative flow fields. This assumes that transient aquifer stresses that are not simulated would not produce significantly different results;
- Estimated capture well pumping rates are representative of actual rates;
- Flow in fractured bedrock can be approximated as an equivalent porous medium;
- Vertical discretization within the model is fine enough to capture the depth-specific flow fields;
- The range of aquifer properties estimated from field-based data provides a reasonable range of site values that are representative of actual site conditions; and
- Any unknown water management practices of adjoining properties (e.g., possible groundwater abstraction or land application of water) do not significantly impact the groundwater system in the Stage I and II areas.

There is a degree of uncertainty inherent in any model and its application. In this case, there is uncertainty associated with model inputs such as pond seepage rates, pumping rates, areal recharge, and

hydraulic properties. The model includes an underlying assumption that the aquifer inhomogeneity and anisotropy can be adequately characterized with an appropriate choice of aquifer properties and grid size. Sedimentary processes that formed inter-fingered sandstone, shale, mudstone and coal strata in the Fort Union Formation likely created changes in vertical and horizontal hydraulic properties on the scale of tens of feet or less. In addition, the model assumes that flow in bedrock units is horizontally isotropic and therefore it does not simulate any undocumented preferential flow paths that could be present. The process of strip-mining and backfilling of pits with spoils which occurred in areas within the edge of the model domain creates a heterogeneous distribution of materials at many scales which, along with layering and inter-fingering of alluvial and colluvial units, results in heterogeneity at tens of feet or less.

The ability of the model to accurately predict changes in groundwater flow and advective transport at the scale of tens of feet or less may be limited, especially in areas with complex flow characteristics. For these reasons, model predictions should not be viewed as certainties but as the best interpretation of likely outcomes based on available information and data. Additional lines of evidence, such as field-measurements of drawdown and trends in water quality, should be assessed along with the model predictions to evaluate capture system performance.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Calibration of the numerical groundwater flow model described in this report demonstrates the model is capable of simulating groundwater flow and advective transport under a variety of hydrogeologic conditions. The numerical model is appropriate for use in evaluating elements of the conceptual model and the efficacy of groundwater capture systems, either currently operating or being considered in the future.

Development of the conceptual and numerical groundwater flow model, along with model calibration, model sensitivity analysis, and capture analysis, have led to the following conclusions:

- The STEP and SOEP area has a complex and dynamic groundwater flow system. In addition to complex hydrostratigraphy and diverging groundwater flow, infiltration through the reclaimed SOEP and seepage from cells in the STEP and Surge Pond influence groundwater flow in the area.
- Groundwater quality that has been influenced by SOEP and STEP is characterized by elevated levels of certain parameters, including dissolved boron, chloride, sulfate, magnesium, and SC.
- Vertical gradients for measured paired wells are generally downward across the site.
- Much of seepage from the SOEP and STEP infiltrates into underlying alluvium and bedrock and flows northeast toward East Fork Armells Creek. In 2004, groundwater exceeding BSLs flowed into East Fork Armells Creek alluvium and then northwest parallel to the creek. In the last several years, the groundwater capture system has cut off the plume in groundwater beneath the drainage east of the STEP Main Dam before it enters East Fork Armells Creek alluvium. Some groundwater exceeding BSLs has migrated a small way north of the STEP although migration in this area appears to be very slow. A small area of uncaptured bedrock and alluvial groundwater exceeding BSLs is located south of the SOEP and West of the Surge Pond.
- BSLs recently recalculated for area groundwater are in some cases substantially lower than previously estimated BSLs. In particular, the chloride BSL for alluvium dropped from 213 mg/L to 45 mg/L, which results in the extent of chloride exceeding the BSL in East Fork Armells Creek alluvium being much larger than the extents for dissolved boron, sulfate and SC. Some chloride detected in East Fork Armells Creek alluvium, particularly south of the STEP, could originate from sources other than the SOEP and STEP, and the ponds may not be the source of chloride detected in that area. Some of the chloride detected in most alluvial wells in East Fork Armells Creek downgradient of the STEP might have originated from the SOEP or STEP prior to the full buildout of the capture system.
- Between 2005 and 2014, installation of several alluvial and bedrock capture wells and rehabilitation of well 360A between the STEP Main Dam and East Fork Armells Creek improved groundwater capture system effectiveness thereby reducing concentration of indicator parameters in alluvium and bedrock well in this area.
- Concentrations of indicator parameters in alluvial monitoring wells east of Cell D (377A, 382A, 994A, 997A and 998A) exhibit decreasing trends indicating that groundwater capture wells

installed in this area since 2008 are effectively capturing groundwater prior to its reaching East Fork Armells Creek alluvium.

- The numerical groundwater flow model has been calibrated to multiple sets of hydrogeologic data that represent a range of conditions and is able to reproduce flow fields, heads, and fluxes within a reasonable range of error under a variety of hydrologic stresses. This robust calibration procedure provides confidence in the predictive capabilities of the model.
- The model calibration is most sensitive to increases in horizontal hydraulic conductivity and pond seepage rates.
- Analysis indicates the capture system is currently capturing all groundwater originating from the SOEP and STEP that flows east of the STEP Main Dam in 50 years before it reaches alluvium associated with East Fork Armells Creek. Groundwater exceeding BSLs in alluvial monitoring wells adjacent to East Fork Armells Creek is likely either residual from before the implementation of the latest capture system or is from sources other than the SOEP and STEP.
- Capture analysis indicates particles within an area where groundwater exceeds BSLs for indicator parameters in the northwest portion of the SOEP area are partially captured by wells 2024D, EAP-205, 375D, and 376D. According to the model, some uncaptured particles in this area travel north toward monitoring wells 354D, 2025D, 2026D, and 2031D. However, groundwater samples from these wells do not currently exceed BSLs for indicator parameters.
- Particles representing groundwater originating in the northwest half of the SOEP area are partially captured by wells 2024D, EAP-205, 375D, and 376D. Particles released north of this area near wells 903D, 2032D, 2033D and 929D are not captured (although many particles released south of this area are captured by well 2024D). The model indicates that particles that are not captured in this area would move north toward well 355D, which has not exhibited evidence of process pond impacts.
- Capture analysis indicates particles within an area where groundwater exceeds BSLs for indicator parameters immediately north of STEP Cell A and Cell B near wells 2022D and 2023D are not captured. The model indicates that particles originating near 2022D travel north toward wells 398D, 399D, and 901D, and particles originating near 2023D travel north toward 2009D. Groundwater samples from wells 398D, 399D, 901D have not exceeded BSLs, and samples from well 2009D slightly exceed the BSL for sulfate but not BSLs for dissolved boron, chloride or SC. However, there are no indications of impacts from process water at this location, as sulfate levels have shown a slight decline while all other indicators are stable.
- Groundwater that exceeds BSLs in areas north of the SOEP and STEP appears to be moving very slowly due to relatively low permeability (with the exception of near well 2024D). This results in low yield wells and is a major reason for lack of complete capture in this area.
- The capture system below the STEP dam effectively cuts off contaminated source water from traveling east to East Fork Armells Creek Alluvium.
- Results of reverse particle tracking analyses suggest groundwater at wells 366S, 374S, 926S, 977A, 978S, and 979S containing concentrations of indicator parameters exceeding BSLs originates from upland areas south of those wells and not from the SOEP area.

- Uncertainty analysis indicates that predicted groundwater capture analysis is not very sensitive to decreases in capture well pumping rates on the order of 25 percent.

In developing the conceptual and numerical models potential data gaps were identified. NewFields recommends the following work to fill data gaps:

- Even though simulation of plume capture using particle tracking was not sensitive to overall decreases of current capture rates, future capture analyses that might consider fewer active pumping wells and/or lower pumping rates might be sensitive to this parameter. Developing a more accurate method of measuring capture well pumping rates would increase model accuracy.
- The downgradient extent of areas exceeding BSLs between wells 2022D and 2009D is uncertain. Monitoring well(s) should be installed in bedrock between wells 2022D and 2009D to evaluate the downgradient extent of process pond-affected groundwater and the feasibility of additional capture in this area based on well yield.
- Monitoring well(s) should be installed in bedrock north of well 2032D to evaluate the downgradient extent of process pond-affected groundwater and the feasibility of additional capture in this area based on well yield. Screening wells or extending sand-pack around the screen over a larger saturated interval than 2032D would accommodate potential capture.
- It appears more capture is needed near well 903D based on concentrations of parameters exceeding the updated BSLs. It is recommended the feasibility of converting 903D to a capture well be evaluated. If this is not feasible, installation of an additional well in this area should be considered to evaluate feasibility of additional capture based on well yield.

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