BGC ENGINEERING USA INC.
AN APPLIED EARTH SCIENCES COMPANY

SWCA ENVIRONMENTAL CONSULTANTS

RESOLUTION COPPER PROJECT EIS

REVIEW OF NUMERICAL GROUNDWATER MODEL CONSTRUCTION AND APPROACH (MINING AND SUBSIDENCE AREA)

DRAFT

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November 1, 2018
Project No.: 1704005.03

Mr. Chris Garrett
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20 E Thomas Rd, Suite 1700
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Dear Mr. Garrett,

Re: Review of Numerical Groundwater Model Construction and Approach (Mining and Subsidence Area)

This technical memo summarizes the evaluation of the model construction and approach for the groundwater model used to evaluate future groundwater conditions at and surrounding the proposed Resolution Copper panel cave mine. The evaluation was performed for the Resolution Copper Project Environmental Impact Statement (EIS) Groundwater Modeling Workgroup.

Yours sincerely,

BGC ENGINEERING USA INC.
per:

Gabriele Walser, Ph.D.
Senior Hydrologist/Engineer

DEFINITIONS AND CONCEPTS

Conceptual Model: A conceptual model describes the major components of the site's hydrologic system and the processes that link them. The conceptual model components generally include: topography; geology; hydrogeological properties of aquifers and aquitards; surface water hydrology including surface-water bodies; climate and vegetation, including precipitation (i.e., snow and rain), evapotranspiration and recharge rates and distributions in time and space; groundwater pumping rates and other boundary conditions; and, characterization of the dominant physical processes of water moving through the groundwater system. A conceptual model is alternately referred to as a hydrogeologic conceptual model, hydrologic conceptual model, or conceptual site model.

Numerical Model: A numerical model implements the conceptual model.

Steady-state modeling period: The steady-state modeling period refers to the period of time when all groundwater flow is assumed to be at steady state (i.e., inflows equal outflows, without any change in groundwater storage) over the timescale of a few years, during which time inter-annual seasonal variations in storage are assumed to balance. For the project area, the steady state period is assumed to occur before any mine dewatering activities started, because mine dewatering activities remove more water from storage than is replenished by precipitation. For modeling purposes, the year 1910 was assumed to represent pre-mining steady-state conditions.

Transient modeling period: The transient modeling period includes all time periods simulated that are not steady state, i.e., inflows are not equal to outflows, and a change in groundwater storage in the model area occurs. Dewatering would cause a decrease in groundwater storage in the model area.

Steady state calibration: During steady state calibration, model parameters (hydraulic conductivity, recharge, and others) are adjusted to match observed heads or fluxes under steady state conditions.

Transient calibration: During transient calibration, model parameters (hydraulic conductivity, recharge, and others) are adjusted to match observed heads or fluxes over time. Storage parameters can only be adjusted during transient calibration.

Transient calibration period: The transient calibration period refers to the period when observed heads and/or fluxes can be used for the transient calibration. For the project, this refers to the time from 1998 through 2016.

Current conditions: For purposes of the groundwater model, current conditions refer to conditions in 2016.

Predictive modeling period: The predictive modeling period includes future time periods for which the model makes predictions about groundwater flow and heads. The predictive modeling period includes the time period in which mining activities occur, and a time period after mining activities, during which the groundwater system may return to steady state conditions.

Life of mine phases: The life of mine phases are the time periods in which the mining activities occur, with each phase signifying a new or a change in mining activity. Future life of mine phases are simulated during the predictive modeling period.

EXECUTIVE SUMMARY

This technical memo summarizes the evaluation of the model construction and approach for the groundwater model used to evaluate future groundwater conditions at and surrounding the proposed Resolution Copper panel cave mine. The groundwater model does not consider impacts from the future tailings facility or water supply pumping over 5 miles distant from the site, these impacts have been considered and evaluated separately.

The evaluation was performed for the Resolution Copper Project Environmental Impact Statement (EIS) Groundwater Modeling Workgroup. The Groundwater Modeling Workgroup is composed of specialists from the Forest Service and cooperating agencies, the EIS third-party contactor SWCA and subcontractors, including BGC Engineering Inc. (BGC), as well as the applicant, Resolution Copper Mine (Resolution Copper) and their contractors. The modeling was performed by WSP, USA (WSP), a contractor for Resolution Copper.

This review concludes that WSP's approach to simulating potential groundwater drawdown impacts caused by mining and subsidence follows best practices and is appropriate and reasonable. The use of MODFLOW-SURFACT follows common mining industry practice, and the reviewed conceptual model and the setup of the numerical model are appropriate and reasonable.

BGC and the Groundwater Modeling Working Group additionally conclude that the results of the predictive groundwater model appear reasonable and are based on best available science and understanding of the hydrogeology and project at the time the groundwater model was created. Because estimated parameters are inherently uncertain, a sensitivity analysis was conducted to estimate the potential range of impacts. This review concludes that the range of conditions considered by the sensitivity analysis is reasonable.

Ongoing groundwater monitoring should be conducted to enable further evaluation and updates of the model and its assumptions. Similarly, the groundwater model should be updated as understanding of the project development is refined.

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LIMITATIONS

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1.0 INTRODUCTION

Resolution Copper proposes to construct and operate an underground copper mine (project) near Superior, Arizona, using an underground mining method known as panel caving. The depth of the copper deposit ranges from about 4,500 to 7,000 feet (ft) below ground surface (bgs), with a thickness locally greater than 1,600 ft. The footprint area of the orebody is approximately 2.7 square miles. Surface subsidence of up to 1100 feet above the ore deposit is anticipated as a consequence of the panel caving (Itasca 2017). The mine is expected to take 9 years to construct, have a 40-year operational life (which overlaps the last 3 years of construction), followed by 5 to 10 years of reclamation, for a total mine life of approximately 51 to 56 years. Historic mining in the project area started in the late 1800s and intensified in 1910 with the creation of the Magma Mine. Dewatering to enable underground mining began in 1910 and will increase with the proposed project.

The U.S. Forest Service (Forest Service) is the responsible agency to prepare an Environmental Impact Statement (EIS) under the National Environmental Policy Act (NEPA) to assess impacts of the proposed mining operations.

WSP (2019) created a groundwater model to address issues regarding impacts to water resources raised during public scoping; to support and validate conceptual understanding of the hydrogeologic system; to evaluate and predict future hydrogeologic impacts from the proposed Resolution Mine during construction, operation and post closure; and to inform the hydrogeologic monitoring program.

A groundwater modeling work group (GMWG) was created after the Forest Service determined that the most appropriate approach to review the groundwater modeling work would be to collaboratively review the modeling approaches and results with stakeholders. Regular meetings of the groundwater modeling work group were held starting in September 2017. Regular attendees included Forest Service, third-party specialists contracted to prepare the NEPA documents (SWCA Environmental Consultants, HydroGeo Inc., BGC Engineering Inc., and other subcontractors), Resolution Copper and contractors (WSP, Montgomery & Associates), Arizona Department of Water Resources, Arizona Game and Fish Department, specialists on behalf of the San Carlos Apache Tribe, and U.S. Environmental Protection Agency. The complete list of attendees can be found in Appendix A. The groundwater model review process included an iterative process of developing specific action items and data requests, receiving data submittals from Resolution Copper, and reviewing the data requests collaboratively as a group.

The purpose of this memo is to summarize the findings of the groundwater modeling work group regarding the review the groundwater model prepared for the project by WSP (WSP 2019). This memo includes the professional opinion of BGC Engineering Inc. (BGC), as well as the opinion of the groundwater modeling work group (GMWG). Where the work group did not come to an agreement, different opinions are noted in the document.

1.1. ISSUES TO BE ADDRESSED BY THE GROUNDWATER MODEL

The Groundwater Model Workgroup identified the following issue factors (Issues) to be addressed by the groundwater model (SWCA, 2016).

- 6A-1. Quantitative assessment of direction and magnitude of change in aquifer water level, compared with background conditions.
- 6A-2. Geographic extent in which water resources may be impacted.
- 6A-3. Duration of the effect (in years).
- 6A-5. Number of known private and public water supply wells within the geographic extent of the water-level impact, and assessment of impact to these water supplies (feet of water-level decrease).
- 6C-2. Quantitative assessment of potential lowering of the water table/reduced groundwater flow to Queen Creek, Devil's Canyon, Arnett Creek, Mineral Creek, or other perennial waters that results in permanent changes in flow patterns and that may affect current designated uses.

2.0 STANDARDS AND BEST PRACTICES TO CONSIDER

Following are the main documents referenced in this memo.

2.1. American Society for Testing and Materials (ASTM) Standards

- ASTM D5979-96(2014), Standard Guide for Conceptualization and Characterization of Groundwater Systems (2014)
- ASTM D5447-17, Standard Guide for Application of a Numerical Groundwater Flow Model to a Site-Specific Problem (2017)
- ASTM D5490-93(2014)e1, Standard Guide for Comparing Groundwater Flow Model Simulations to Site-Specific Information (2014)
- ASTM D5609-16, Standard Guide for Defining Boundary Conditions in Groundwater Flow Modeling (2016)

- ASTM D5610-94(2014), Standard Guide for Defining Initial Conditions in Groundwater Flow Modeling (2014)
- ASTM D5981/D5981M-18, Standard Guide for Calibrating a Groundwater Flow Model Application (2018).
- ASTM D5611-94(2016) Standard Guide for Conducting a Sensitivity Analysis for a Groundwater Flow Model Application (2016)
- ASTM D5718-13 Standard Guide for Documenting a Groundwater Flow Model Application (2013)
- ASTM D653-14, Standard Terminology Relating to Soil, Rock, and Contained Fluids (2014)

2.2. Description of Best Practices

- Applied Groundwater Modeling, Simulation of Flow and Advective Transport, (Anderson, et al., 2015.
- USGS Scientific Investigations Report: Guidelines for Evaluating Ground-Water Flow Models, (Reilly and Harbaugh, 2004).
- Groundwater Modeling Guidance for Mining Activities, Nevada Bureau of Land Management, (BLM, 2008).
- Technical Guide to Managing Ground Water Resources, (USFS, 2007).
- Australian groundwater modelling guidelines, (Barnett et al., 2012).
- Hydrogeology in practice: a guide to characterizing ground water systems, (Stone, 1999)
- Guidance on the Development, Evaluation, and Application of Environmental Models (EPA, 2009)
- Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities (Wells et al., 2012)

2.3. Adherence of Resolution Groundwater Modeling Process to Standards

The standards and best practices described above are rarely prescriptive; they do not dictate the specific technical choices that must be made by the modelers. Instead, these documents describe the general process steps that are considered a standard of practice and identify some common considerations that should be explored as part of that process.

The modeling process employed for the Resolution Copper EIS does not solely consist of the groundwater modeling reports themselves. The modeling process also includes all information that was in front of, discussed, or produced by the Groundwater Modeling Workgroup and the

Forest Service, which is contained in the project record. Specific adherence to standards of practice based on this body of information is described in Appendix 1.

The purpose of Appendix 1 is to document how the modeling process employed for the Resolution Copper EIS followed the appropriate process steps, and to identify where the information can be found in the project record. The purpose of this specific section is not to pass judgment on the appropriateness of modeling choices, which was the wider purpose of the Groundwater Modeling Workgroup and the purpose of this memorandum. Appendix 1 solely documents that the modeling process substantially followed the professional standards in the ASTM standards and other reference documents.

2.4. Site Specific Information and Reports

The hydrogeologic conceptual model was developed using a large amount of site specific exploration data and information from numerous technical reports. The following is a summary of the site-specific information used for the development of the conceptual model:

- Montgomery & Associates
  - Borehole installation and testing
  - Surface water and Spring and seep surveys
  - Recharge, discharge, and water balance assessments
- 4D-Geo
  - Geologic Information
- Applied Structural Geology
  - Summary of Geologic Information Relevant to Development of the Porphyry Cu-Mo Resolution Deposit, Arizona
- Resolution Copper
  - Internal information from exploration borehole and shaft data
  - Internal information from underground exploration data
- WSP
  - Conceptual model
  - Hydrogeologic and hydrostructural units
  - Recharge and discharge rates and water balance

Please refer to Process Memorandum to File, Summary of Hydrologic, Hydrochemical, and Geochemical Data Received to Date, SWCA, October 2017 and addendums.

3.0 DESCRIPTION AND REVIEW OF THE RESOLUTION COPPER GROUNDWATER CONCEPTUAL MODEL

Groundwater modeling must be based on a hydrogeologic conceptual model that includes a simplified hydrogeologic framework and defines pertinent processes that must be quantitatively incorporated into the subsequent numerical modeling. ASTM D5447-17(2017) requires that a conceptual model be created before setting up a numerical model. Anderson, et al. (2015) indicates that building a conceptual model is a crucial step before building a numerical model. The hydrogeologic conceptual model is primarily a qualitative representation of the system of interest and includes information on the geologic and hydrogeologic framework, sources of groundwater recharge and discharge, groundwater flow directions, water balance, boundary conditions, climatologic characteristics, and geochemical characteristics (Anderson et al., 2015). Hydrogeologic conceptual models are iterative and may need to be modified as additional data is collected and as numerical model development, particularly calibration, proceeds (ASTM D5979-96). The iterative processes of conceptual and numerical modeling may also be used to guide additional data collection, which will lead to a more advanced understanding of the groundwater system (NDEP, 2018).

ASTM D5979-96 (2014) and Anderson et al., (2015) recommend that the hydrogeologic conceptual model qualitatively and quantitatively characterize the following major components of the project location and surrounding area:

- Surface Characterization
  - Terrain and boundaries
  - Climatologic characteristics
  - Surface water
  - Water use
- Geologic characterization
  - Stratigraphic and lithologic units
  - Structural geology
- Hydrogeologic characterization
  - Hydrogeologic units
  - Hydrostructural units
- Groundwater system characterization
  - Groundwater recharge
  - Groundwater discharge

- Groundwater budget
- Groundwater flow paths and flow directions,
- Boundary conditions
- Initial conditions

The following sections describe and review the components of the conceptual model and evaluate the completeness and rationale and appropriateness of the surface characterization, the geologic characterization, the hydrogeologic characterization, and the groundwater system characterization.

3.1. Surface Characterization and Model Area

The surface characterization includes the description of anthropogenic and natural features and processes related to water at or near ground surface in the model area (ASTM D5979-96[2014], 2014). The model area must be large enough to encompass the potential water resource impacts associated with the proposed mining activities, and include watershed divides and natural boundary conditions where feasible.

The model area includes the Upper Queen Creek surface watershed and the northwestern part of Mineral Creek – Gila River surface watersheds (10-digit Hydrologic Unit Code) (USGS, 2018). Montgomery & Associates (2018), describe part of the USGS Mineral Creek-Gila River surface watershed as two separate watersheds: Devils Canyon Watershed and Upper Mineral Creek Watershed (**Error! Reference source not found.**).

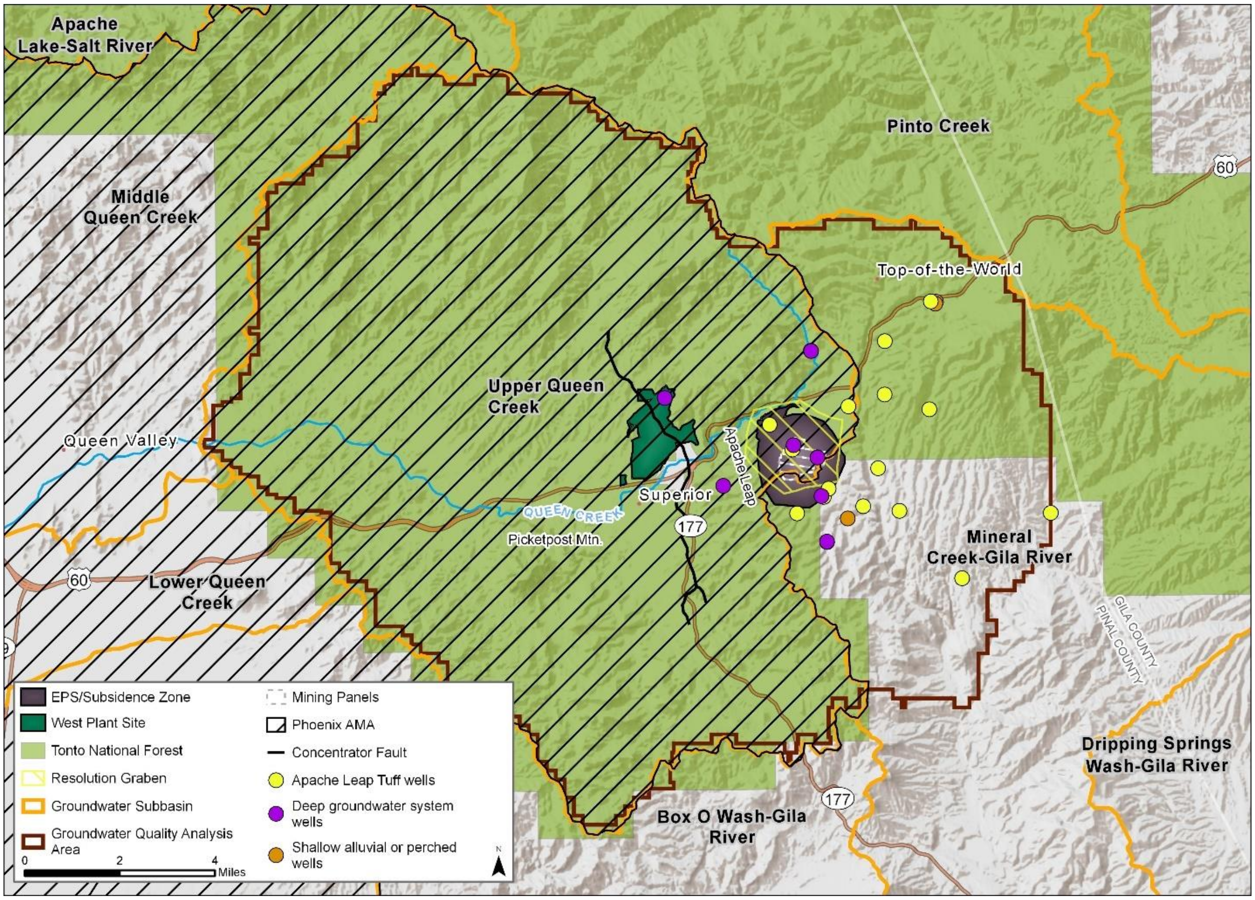

Figure 1. Model Area

3.1.1. Terrain and Boundaries

The groundwater model area incorporates altitudes ranging from 2160 feet to 5520 feet and is therefore subject to substantial climatic variability. The highest point is Montana Mountain in the north of the model area, while the lowest point is Whitlow dam at the eastern end of the model area. Model boundaries follow the Upper Queen Creek surface watershed and part of Mineral Creek – Gila River surface watershed (10-digit Hydrologic Unit Code) (USGS, 2018). Mineral Creek forms the eastern boundary of the groundwater model.

3.1.2. Climatologic Characteristics

Climate of the Superior Basin is arid to semi-arid, with temperatures exceeding 100 degrees Fahrenheit in the summer in the lower elevation areas, and occasionally dipping below freezing in the winter. Precipitation typically occurs in two seasons, with strong, short-duration storms from July through September, and longer-duration storms of moderate intensity from November through March. While the vast majority of this precipitation falls in the form of rain, snowfall can occur in the winter months, particularly at higher elevations.

Resolution Copper maintains a meteorological station in the Superior Basin at its West Plant Site. Precipitation available from Prism Data (Oregon State University, 2012) compare well with precipitation recorded at the West Plant Site (Montgomery & Associates 2017b). PRISM data indicate that precipitation is higher in the lower basins than in the mountains.

3.1.3. Surface Water

Queen Creek is the main drainage in the Upper Queen Creek watershed, which forms the western half of the model area. The outlet of the watershed is the Whitlow Ranch Dam. The dam is in a narrow canyon, where the alluvium is truncated and the bedrock geometry forces groundwater to the surface. This is conceptualized as the exit point for all groundwater and surface water of the Queen Creek watershed. Queen Creek from headwaters to Whitlow Ranch Dam is ephemeral. although in some areas above Superior it may be considered intermittent, as winter base flow does occur and likely derives from seasonal storage of water in streambank alluvium. However, Queen Creek has a perennially flowing reach between kilometers 17.39 and 15.55, which is located downstream from Superior and upstream from Boyce Thompson Arboretum. This flowing reach receives effluent discharge from the Superior Wastewater Treatment Plant. Substantial flow in this reach also derives from dewatering discharges from a small open-pit perlite mining operation, where the mine pit presumably intersects the regional aquifer.

Some tributaries to Queen Creek have short spring-fed saturated reaches, but generally less than 500 feet in length. Queen Creek does form a perennial reservoir at Whitlow Ranch dam, however, absent any large precipitation event, the reservoir has an area of 100 square feet or less. Whitlow Dam is intended as a flood control dam, was not primarily intended to be a water supply reservoir. Streamflow measured at Whitlow Ranch Dam represents groundwater discharge from the Queen Creek floodplain aquifer that is not lost to evapotranspiration or groundwater pumping. The median daily baseflow over the entire study period was 1.43 cubic feet per second. Neither streamflow nor baseflow hydrographs exhibit consistent seasonality over the period of record;

instead, baseflow variability depends primarily on the intensity of winter precipitation. Following exceptionally wet winters, an abrupt rise in Queen Creek baseflow is observed, followed by a recession period lasting from months to years (Montgomery & Associates 2017b).

Mineral Creek drains the eastern half of the model area and forms the boundary of the model area. A dam creates a reservoir where Mineral Creek and Devils Canyon meet, which is the lowest point of the western part of the model. Both Mineral Creek and Devils Canyon have continuous flow in their lower reaches. Mineral Creek is connected with the regional aquifer, and perennial flow originates primarily from the Apache Leap Tuff aquifer.

The upper reach of Devil's Canyon includes a reach of perennial flow; however, this section of Devil's Canyon lies above the water table in the Apache Leap Tuff aquifer and is most likely supported by snowmelt or precipitation stored in near-surface fractures, and/or floodwaters that have been stored in shallow alluvium along the stream. Further downstream in Devil's Canyon, perennial streamflow occurs again. Flow there arises both from discrete springs along the walls of the canyon (four total), as well as groundwater inflow along the channel bottom. These waters arise primarily from the Apache Leap Tuff aquifer. Streamflow in middle and lower Devil's Canyon is connected with the regional aquifer.

3.1.4. Water Use

A significant amount of groundwater use in the model area is for mining and dewatering of mining operations. Historical pumping for mine dewatering operations occurred east of the Concentrator Fault, mainly at the Silver King Mine, the Lake Superior and Arizona (LS&A) Mine, and the Belmont Mine. Large-scale dewatering began in 1910 at Shaft No.1 for the Magma Mine, also located east of the Concentrator Fault. Dewatering of the Magma Mine was roughly continuous from 1910 until 1998, except for the period between 1986 and 1989 when no significant pumping occurred. Although active mining in the Magma Mine ceased on June 30, 1996, the underground mine dewatering system remained in operation until 1998, when the dewatering pumps in the mine were shut off.

Following the shutdown of the dewatering system on May 6, 1998, the rising water levels were monitored. The 2009 water levels (2,100 ft amsl) were still below the pre-1910 water levels (about 3,150 ft amsl). Dewatering was resumed on March 17, 2009 at the East Plant Site (east of the Concentrator Fault). Currently, dewatering is ongoing and dewatering rates and water levels are continuously monitored.

Other water users in the study area include companies, utilities, and individuals requiring water supply for use in mining, ranching, potable water supply, stock, and irrigation for agriculture and for Boyce Thompson Arboretum (BTA). Most of these water users are in Queen Creek watershed. Water for the town of Superior is provided by the Arizona Water Company, with water derived from outside the model area.

3.1.5. Rationale and Appropriateness of the Surface Characterization

Resolution Copper and their contractors, particularly Montgomery & Associates, collected a large amount of information characterizing terrain and boundaries, climatologic characteristics, surface water, and water use in the model area. The surface characterization contains all the information pertinent to the model area and recommended to be collected by ASTM standard D5979 (ASTM 2014). BGC and the GWMG concurs with the surface characterization that Resolution Copper has presented and considers the information sufficient for the groundwater model.

3.2. Geologic Characterization

The Superior Basin, which underlies the western part of the model area, is comprised of a large, east-tilting block bounded by two major north-northwest trending, normal faults that dip to the west: Elephant Butte Fault and Concentrator Fault. These faults are interpreted to largely control the pattern of geologic units exposed at land surface and their distribution in the sub-surface.

The geologic interpretations used for the conceptual hydrogeologic model is presented in:

- 4DGeo – Applied Structural Geology, 2017. Summary of Geologic Information Relevant to Development of the Porphyry Cu-Mo Resolution Deposit, Arizona. Report prepared for Resolution Copper Mining LLC, May 2017, 58 p. This study presents the most up to date analysis of the subsurface geology of the project area.

3.2.1. Stratigraphic and Lithologic Units

Study area stratigraphic and lithologic units have been well defined and delineated from extensive borehole and historical and existing mine workings data (4DGeo, 2017). Resolution Copper created a detailed Vulcan model with stratigraphic and lithologic units of the western half of the model area. Montgomery & Associates translated stratigraphy and lithology of the western half of the model area into a Leapfrog model.

3.2.2. Structure

Study area subsurface structure, including fault locations, geometries, and offsets has also been well defined and delineated using borehole and mine workings data (4DGeo, 2017). Anthropogenic features such as mine workings and shafts are also characterized as part of the subsurface structure.

3.2.3. Rationale and Appropriateness of the Geologic Characterization

Resolution Copper and past mine operators, as well as the USGS and others, have compiled a vast amount of information and data about the geology in the project area (4DGeo, 2017). The geologic characterization also follows the general recommendations of the ASTM standards (ASTM, 2014a and 2017) as well the guidelines presented in USGS, 2004, Anderson et al., 2015, and NDEP, 2018. BGC and the GWMG concur with the geologic characterization that Resolution Copper has presented.

3.3. Hydrogeologic Characterization

The project area includes the following two regional groundwater zones:

- Area east of the Concentrator Fault, with
    - Shallow Groundwater System
    - Apache Leap Aquifer
    - Deep Groundwater System
- Area west of the Concentrator Fault, with
    - Shallow Groundwater System, including the floodplain alluvium along Queen Creek and the low permeable basin fill sediments
    - Deep Groundwater System, including the deep geologic units near Superior, AZ.

Characterization of the geology and hydrogeology indicates that the Concentrator Fault, located to the north and east of the WPS, acts as a barrier to groundwater movement between the shallow and intermediate-depth groundwater systems underlying WPS and East Plant Site (EPS) areas. Less information is available on the deep groundwater systems underlying both areas; however, based on a lack of water level response to mine dewatering activities and large differences in hydraulic head across the fault, the hydraulic connection of the deep groundwater systems across the Concentrator Fault is limited to where historic mine workings locally cross the fault.

3.3.1. Hydrogeologic Units

Hydrogeologic units are defined and delineated by hydrologic properties, including porosity, permeability, hydraulic conductivity (or soil moisture characteristic functions), transmissivity, and storativity (WSP, 2017, amended 2018). Hydrogeologic units may or may not correspond directly to geologic stratigraphic or lithologic units.

Based on these hydrologic properties, ten Hydrogeologic Units are defined in the conceptual model (WSP, 2017);

1. Quaternary Alluvium (Qal), is the same as the geologic unit.
2. Quaternary-Tertiary Gila Conglomerate (QTg), is the same as the geologic unit.
3. Tertiary Volcanics – Younger (Tvy), Geologic units that are classified as Tvy include units Tb, Tt, Tfp, Tftp, and Tfpi (Spencer and Richard, 1995). These units are part of the Gila Group volcanic rocks of the Superstition Volcanic Field (Ferguson and Skotnicki, 2001) and include basaltic lavas (Tb) and felsic tuff (Tt) interbedded with the Tcg, and Picketpost Mountain Formation felsic lavas, tuffs, and hypabyssal intrusives (Tfp, Tfpt, and Tfpi, respectively).
4. Tertiary Apache Leap Tuff (Tal), same as geologic unit.
5. Tertiary Volcanics – Older (Tvo), Geologic units that are classified as Tvo represent early Miocene age volcanic rocks that predate the Apache Leap Tuff. These include, felsic lavas and associated tuffs (Trdu and Trdt), rhyodacite lava (Trw), intermediate to mafic lavas (Tdm) in the northwestern part of the study area, and undifferentiated volcanic rocks (Tev) in the northeastern part of the study area. The formations form part of the Superstition Group volcanic rocks.
6. Tertiary Whitetail Conglomerate (Tw), same as geologic unit.
7. Cretaceous Volcaniclastics (Kvs), geologic units that are classified as Kvs consists of a sequence of volcaniclastic sedimentary rocks (Kvs; graywacke, conglomerate, lava flows and tuff, andesitic, rhyodacitic and dacitic) and quartzose sediments (Kqs; sandstone and siltstone). These rocks are found only within the graben area underneath the Whitetail Conglomerate.
8. Paleozoic Sediments – Undifferentiated (Pz), geologic units that are classified as Pz consists of the Cambrian Bolsa Quartzite (Cb), Devonian Martin Formation (Dm; chiefly dolomite and dolomitic limestone), Mississippian Escabrosa Limestone (Me) and Pennsylvanian-Permian Naco Limestone (Pn).
9. Precambrian Apache Group – Undifferentiated (pЄy), The geologic units of the pЄy include the Precambrian Apache Group, Troy Quartzite, and diabase.
10. Precambrian Pinal Schist (pЄpi), same as the geologic unit.

3.3.1.1. Isotropy/Anisotropy

All units, apart from the Tal, are conceptualized as isotropic in the horizontal direction, hence the range in values is due to heterogeneity.

The Tal is the most significant hydrogeologic unit in the East Plant Site and mine area, and most of the available aquifer testing data come from this unit. After a 90-day pumping test in the Devils Canyon Area, observed drawdown in the Tal was strongly asymmetric with a north-south orientation; the largest drawdown was observed to the north and south of the pumped well. Therefore, the Tal, is characterized as anisotropic in both the horizontal and vertical directions (Montgomery & Associates, 2014).

There are fewer aquifer test data for the other nine hydrogeologic units. These units are thus characterized as being isotropic in the horizontal direction and having little to no anisotropy in the vertical direction.

3.3.1.2. Hydrologic Response (Aquifer/Confining Unit)

Based on hydraulic conductivity, saturated thickness, and continuity, hydrogeologic units can be characterized as either aquifers or confining units, or some combination. The Apache Leap Tuff is the most significant aquifer in the project area. Whitetail Conglomerate, due to its low permeability, has been characterized as a confining unit that separates the shallow aquifer (including aquifers in alluvium, Apache Leap Tuff, and tertiary volcanic rocks), from the deep bedrock groundwater system (including cretaceous and Paleozoic rock aquifers, and the Apache group aquifers). West of the Concentrator fault, the Gila Conglomerate is characterized as an aquifer, however, it has limited permeability, and mudstone lenses within the Gila Conglomerate can act as confining units.

3.3.2. Hydrostructural Units

Hydrostructural units are structural features such as faults, fracture zones, or underground workings that exhibit unique hydrologic properties from the surrounding rock.

Eight named faults are characterized in the conceptual model:

1. North Boundary.
2. Rancho Rio.
3. South Boundary.
4. West Boundary.
5. Concentrator.

6. Conley Springs.
7. Anxiety.
8. Pre-Laramide.

The mine workings and shafts are also considered as individual hydrostructural units.

3.3.2.1. Continuity, Geometry Spatial Distribution, and Thickness

The continuity, geometry, spatial distribution, and thickness of the hydrostructural units have been delineated by borehole and mine workings data and by the results of aquifer tests.

3.3.2.2. Isotropy/Anisotropy

The hydrostructural units have been characterized as isotropic, with the exception of the Anxiety Fault, which is hypothesized to show conduit-like behavior along its strike and greater impedance across it. As such, the Anxiety Fault is characterized and modeled as horizontally anisotropic.

3.3.2.3. Hydrologic Response

The faults within the study area have been generally characterized as behaving as weak, or leaky barriers to groundwater flow. Dewatering inside the Resolution Graben, which is bounded by major faults, has shown only muted impacts outside the Graben. The faults are considered to have hydraulic conductivities that are similar, but lower than the surrounding strata.

3.3.3. Rationale and Appropriateness of the Hydrogeologic Characterization

The hydrogeologic model follows the general recommendations of the ASTM standards (ASTM, 2014a and 2017) as well the guidelines presented in USGS, 2004, Anderson et al., 2015, and NDEP, 2018. The conceptual model is based on site exploration and multiple reports.

BGC and the GWMG concur that the hydrostratigraphic and hydrostructural units have been appropriately conceptualized using available site specific geologic and hydrogeologic test boreholes, hydrologic testing, historic mining data, and current underground exploration mine and shaft data.

Note that evaluation of the geologic and hydrogeologic conceptual model extends well beyond just the groundwater model. Substantial review of the available geologic and geotechnical information has been conducted by a Geology and Subsidence Workgroup (Geology Workgroup), which was formed by the Resolution Copper Project EIS team in order to review RCM's procedures, data, and geologic and geotechnical baseline documents and subsidence model.

This review by the Geology Workgroup is directly relevant to the groundwater model review, in that it included the geologic framework, supporting geologic data, and the location and effect of the major bounding faults. The Geology Workgroup's review is documented in a *Geologic Data and Subsidence Modeling Evaluation Report* (SWCA, 2018).

3.4. Groundwater System Characterization

3.4.1. Groundwater Recharge

In the project area, only a small percentage of the precipitation entering the watershed is available for infiltration. Evaporation removes approximately 90% of the water from precipitation, with runoff and infiltration accounting for the remaining 10%. Woodhouse (1997) found that approximately 2.5 to 3.4% of precipitation infiltrated into the ground at a small, 127-acre watershed adjacent to the proposed mine site.

The PRISM precipitation (Oregon State University, 2012) for the groundwater model ranges from 13 in/year to 25 in/year. Wickham GeoGroup (2015) suggested that recharge should be distributed based on topographic elevation and that recharge should be divided into two zones: one that represents "higher" elevation, and a second that represents "lower elevations", with the break between high and low elevation zones at an elevation of 3600 ft amsl. This results in precipitation of 16 - 17 inch/year for the lower elevation and 23 inch/year for the higher elevation.

For the higher elevation area, 3% of precipitation is an approximate value for recharge based on Woodhouse (1997), and results in a recharge rate of 0.00016 foot/day. For the lower elevation area, 1% of precipitation as an approximate value for recharge was suggested by Wickham GeoGroup (2015), resulting in a recharge rate of 0.000037 foot/day. Additionally, higher recharge in stream channels is likely for Devils Canyon, Mineral Creek and Queen Creek.

3.4.2. Groundwater Discharge

Groundwater discharge can occur at springs or gaining reaches of streams. Diffuse groundwater discharge may also occur as evapotranspiration where the water table is close to the land surface. In the upper Queen Creek watershed, shallow groundwater discharge is likely to be through evapotranspiration along the bottom of Queen Creek and its tributaries and some small springs, but the primary groundwater discharge point is at the west end of the basin at Whitlow Ranch Dam where groundwater is forced to the surface.

Several hydrologic surveys of the Queen Creek Corridor, Devils Canyon, and Mineral Creek watersheds were completed by Montgomery & Associates (2013 and 2017). These studies are based primarily on field surveys and surface flow monitoring data. The study area includes:

- The Devils Canyon watershed
- The western part of the upper Mineral Creek watershed from the confluence with Devils Canyon upstream to the Government Springs Ranch and including Lyons Fork
- The Upper Queen Creek watershed from the Town of Superior upstream to the headwaters

The principal objectives of studies were to:

- Evaluate the magnitude and character of streamflow and base flow within the study area
- Identify locations where discharge from the regional groundwater system(s) supports surface water features
- Develop a baseline data set against which future potential impacts from mining may be measured.

Under natural conditions (pre-mining), it is thought that most groundwater discharge from the Apache Leap Tuff occurred where the pre-1910 water table intersected the topography, primarily to springs and seeps along the main drainages of Queen Creek, Devils Canyon, and Mineral Creek. Minor groundwater discharge from the Apache Leap Tuff is currently observed in springs and pools along the frequently wet reaches of Devils Canyon and Mineral Creek, but historically, it is possible that groundwater from the Apache Leap Tuff also discharged to springs and seeps along Queen Creek.

In the Superior Basin, shallow groundwater discharge is likely to be through evapotranspiration along the bottom of Queen Creek and its tributaries, as well as some small springs. Bedrock geology brings groundwater to or near the surface in the Queen Creek headwaters, and near Boyce Thompson Arboretum.The primary groundwater discharge point is at the west end of the basin at Whitlow Ranch Dam where groundwater is forced to the surface and piped through the dam. It is also worth noting that within the Superior Basin and along the length of Queen Creek between Superior and Queen Valley there are numerous groundwater extraction wells.

At present, the only known discharge from the Deep Groundwater System is from pumping of shafts and historic workings.

3.4.3. Groundwater Budget

A preliminary water budget for the Queen Creek Corridor between 1984 and 2010 was completed by Montgomery & Associates (2017a). A finalized water budget for the whole model area was completed by Montgomery & Associates (2018).

The water budget recognizes four separate domains, Queen Creek Watershed, Devils Canyon Watershed, Upper Mineral Creek Watershed, and the Deep Groundwater System East around the underground mine (no other locations have information regarding the deep groundwater system). The water budget considers precipitation, imported water (from outside the domain for municipal and industrial use in the town of Superior), recharge, runoff and streamflow, surface evapotranspiration, groundwater evapotranspiration, groundwater pumping, seepage, and groundwater flow. Detailed results for the water budget are given in Montgomery & Associates (2018). The results show that the deep groundwater system is losing water from storage due to the dewatering activities. Groundwater in Queen Creek watershed may also lose water due to groundwater pumping, and water recharge to the deep groundwater system.

3.4.4. Groundwater Flow Paths and Flow Directions

The conceptual model uses the available monitoring well and piezometer data as well as direct observations during shaft sinking and historic and current underground mine operations to conceptualize reasonable groundwater flow paths and potentiometric surfaces for each of the hydrogeologic and hydrostructural units. Most groundwater movement in the project area occurs by fracture flow (except for flow in the alluvium). However, at the scale of the model, the hydrogeologic units are assumed to behave as equivalent porous media, where the bulk hydraulic behavior of the rocks can be reasonably conceptualized as a continuous porous medium (WSP 2017).

East of the Concentrator Fault, groundwater flow generally follows topography, flowing from higher elevation areas (Top of the World) to lower elevation areas (confluence of Devils Creek and Mineral Creek). Flow in the Apache Leap Tuff is generally north-south from the higher elevation areas to the discharge areas along the lower part of Devils Canyon and Mineral Creek. Historic mining has created a localized groundwater flow system within the Deep Groundwater System, flowing towards the mine workings (WSP 2017).

West of the Concentrator Fault, groundwater flow is generally towards Queen Creek, and Whitlow Ranch Dam (WSP 2017).

3.4.5. Boundary Conditions

Surface watershed boundaries form the northern, western, and southern boundaries of the model area. These topographic boundaries are conceptualized as also being groundwater flow divides with zero groundwater flow across them. Even though surface watershed boundaries do not necessarily correspond to groundwater watersheds, using surface watersheds is common practice within groundwater modeling as it provides good estimates to flow divides (Anderson, Woessner, and Hunt, 2015).

Mineral Creek forms the boundary on the eastern side of the model area. In transient simulations, boundaries may be arbitrarily located distant from the area of interest, as long as the impacts from the project activities will not reach the boundaries (Anderson, Woessner, and Hunt, 2015). Mineral Creek is approximately 5 miles distant from the mine workings and predicted to be distant from any impacts.

3.4.6. Initial Conditions

Potentiometric surface maps for 1910 and 2017 were provided by WSP (2018). Due to historic and ongoing dewatering pumping, groundwater heads in the project area have been decreasing since 1910. The 1910 potentiometric surface represents a steady-state equilibrium prior to the mining dewatering in the area. There are no water levels records from this period for which to compare to, but the resulting heads from the steady state simulation are qualitatively consistent with probable water levels.

The 1910 potentiometric surface provides a consistent starting point for the simulation and provides the initial conditions.

3.4.7. Rationale and Appropriateness for the Groundwater System Characterization

Resolution Copper and their contractors collected a large amount of information characterizing the groundwater system, including recharge, discharge, water budget, flow paths, and boundary and initial conditions in the model area. The groundwater system characterization contains all the information pertinent to the model area and recommended to be collected by ASTM standard D5979 (ASTM 2014). The conceptualization of the potentiometric surface for the groundwater model follows the general recommendations of the ASTM standards (ASTM, 2014a and 2017) as well the guidelines presented in USGS, 2004, Anderson et al., 2015, and NDEP, 2018. BGC and the GWMG concur with the groundwater system characterization presented in WSP (2019) and

Montgomery & Associates (2017b) and considers the information sufficient for the groundwater model.

4.0 DESCRIPTION AND REVIEW OF THE RESOLUTION COPPER GROUNDWATER NUMERICAL MODEL

The following section describe how the conceptual model is translated into the numerical model.

4.1. Model Code

Numerous numerical model codes may be used to simulate groundwater flow. One of the most commonly used models is MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh et al., 2000; Harbaugh, 2005), which utilizes a finite difference approach. Numerous versions and updates of MODFLOW exist, in the public domain as well as the private sector.

4.1.1. Selected Model Code

MODFLOW-SURFACT, Version 4 (HydroGeoLogic, 1996) was used to assess potential groundwater quantity impacts from the project. MODFLOW-SURFACT is based on MODFLOW but has the advantages of being more numerically stable when solving for groundwater flow in systems with steep hydraulic gradients and large differences in hydraulic conductivity across short distances. Groundwater Vistas (GWV) version 6 (Environmental Simulations, Inc. 2017) was used as the pre- and post-processor for model construction and results analysis.

4.1.2. Rationale and Appropriateness

Anderson et al. (2015); Reilly and Harbaugh (2004); and USFS (2007) suggest MODFLOW as an appropriate groundwater model for three-dimensional problems. MODFLOW is a widely accepted, public domain groundwater flow model produced by the United States Geologic Survey (USGS).

MODFLOW- SURFACT is based on MODFLOW. BGC and the GWMG concur that MODFLOW-SURFACT is an appropriate model code to be used for the groundwater model. MODFLOW-SURFACT uses the finite difference numerical method to obtain approximate solutions to the groundwater flow equation, in which a continuous system is broken into discrete points in both space and time and partial derivatives are replaced by the differences in head between these discrete points at the center of each block, or cell. MODFLOW-SURFACT has the following changes from public-domain versions of MODFLOW: It addresses rewetting of drained cell, includes multi-layer handling of pumping wells and contains improved solutions to address numerical dispersion and oscillations. MODFLOW-SURFACT also includes a time-varying material properties module, which was necessary to model the conductivity changes occurring with subsidence in the pit area. Newer public domain MODFLOW versions (MODFLOW-USG) include time-variant material property package, however, MODFLOW-USG was not available (or only available as a not-fully-tested beta version) when modeling for this project was initiated.

Although the system is fractured rock, it would not be practical to model the groundwater system with a discrete fracture or dual porosity simulator due to the regional scale of the likely impacts. BGC and the GWMG concur that an Equivalent Porous Medium (EPM) approximation is a reasonable approach.

4.2. Model Domain

Establishing the model domain is the first step in developing a numerical model (Anderson et al., 2015). The model domain must be large enough to encompass the potential water resource impacts associated with the proposed mining activities and model boundaries must be situated far enough from disturbance sites to minimize the influence of boundary conditions on simulation results.

The groundwater model area must include all watersheds where mining activities will occur and all watersheds where the groundwater effects from mining would occur. Should preliminary modeling results indicate the project impacts extend close to initially set boundaries, the model area may have to be expanded; conversely, should project impacts remain distant from model boundaries, it may be possible to decrease the model area (or to increase cell size near the model boundaries) to increase modeling efficiency.

The model domain encompasses two regional groundwater systems, subdivided into shallow and deep groundwater systems. In the numerical model, the different groundwater systems are created through the difference in ground surface elevation and hydrogeologic unit elevations across the fault, and through the change in conductivities from different units that are juxtaposed across the fault. The implementation of faults in the numerical model is discussed later.

4.2.1. Selected Model Domain

The purpose of this groundwater model is to model the impacts related to panel caving and subsidence, which create rubblized material with higher conductivities, and dewatering activities related to ore removal. This groundwater model does not attempt to include impacts from the tailings facility or more distant water supply pumping. The model area was selected accordingly, and includes Hewitt Canyon, Potts Canyon, part of the Alamo Canyon-Queen Creek, Silver King

Wash-Queen Creek watershed, Devils Canyon Watershed, and parts of the Upper Mineral Creek and Lyons Fork watersheds (NHD HUC 12 watersheds.)

Modeling results indicated the project impacts extend to the boundaries in the north and south of the model domain. The impacts of these boundaries were tested during the sensitivity analysis, by assuming no-flow boundaries. Drawdowns with no-flow boundaries in place are disclosed in the results, these impacts represent worst-case scenarios for the size of the drawdown cone in the project area.

4.2.2. Rationale and Appropriateness

ASTM D5447-17(2017) indicates that a model area is appropriate, if it can be used to answer the study objectives. The model area must be large enough to show the maximum geographic extent in which water resources may be impacted (Issue 6A-2). Since the maximum geographic extent of impacts is not known before the modeling exercise, the model area is based on best expert judgement of the extent but may have to be modified if model results indicate a much large extent of impacts.

BGC and the GWMG concur that the groundwater model area is appropriate with the following caveats:

A smaller model area that excludes parts of the eastern portion of the model domain, including Hewitt Canyon, Potts Canyon, part of the Alamo Canyon-Queen Creek would also be appropriate to captures changes in groundwater quantity in and around the proposed mining area and include groundwater discharge into historic mine workings, as well as groundwater discharge areas along Devils Canyon and lower Mineral Creek.

The model boundaries to the north and south of the project area are close to the projected impacts. A larger model area might be appropriate, however, BGC and GWMG are satisfied that sensitivity modeling in lieu of extending the model boundaries is adequate.

4.3. Model Grid

Grid design is focused on grid orientation, scale and linking the grid to the real-world site. For anisotropic conditions, grids are generally orientated such that axes are collinear with the diagonal terms of the hydraulic conductivity tensor. If flow is isotropic ($K_x = K_y$), then the grid is typically aligned to decrease the number of active cells and to coincide with natural boundaries, such as topographic flow divides or streams, and in the primary direction of flow.

The scale of grid discretization depends upon several factors, including the expected change in water level over the model domain. Large changes in water levels will require smaller cells (more nodes). Similarly, the greater the spatial heterogeneity, the greater the number of nodes needed. It is important to maintain a grid scale that allows proper representation of hydrologic features, including wells, surface water bodies, spatially variable recharge, as well as fault length and thickness. Also, it is important that the size of the cell adequately portrays the representative elementary volume (REV). REV refers to the scale at which a cube of porous material is large enough to represent the properties of that porous material, but small enough that a change in head in that volume is relatively small. Within the REV, groundwater flow is treated as a continuum and one needs to define effective hydraulic properties of hydraulic conductivity and storage for the size of the REV.

Computational efficiency is linked to the number of cells and heterogeneity. In general, models with fewer than 10,000 cells are very efficient, but it is possible to simulate over 1,000,000 cells. Techniques are available under these circumstances to provide a finer resolution but limit the number of cells. These include cell refinement in regions of significant head change as well as telescopic mesh refinement.

4.3.1. Selected Model Grid

The groundwater model has a minimum grid size of 200 feet by 200 feet. The minimum grid size is maintained in the mine area, but it expands outside the mine area

4.3.2. Rationale and Appropriateness

Anderson et al. (2015) state that the size of the grid spacing needs to be a compromise between accuracy and practicality. A minimum cell size of 200 feet by 200 feet is, therefore, a reasonable compromise, with the caveat that the region of 200 feet by 200 feet cells might needs to be expanded to include Devils Canyon. Cell size can increase towards other boundaries, following the guideline of having a 50% or less increase from one cell to the next (Environmental Simulations, Inc. 2017), to maintain numerical stability and accuracy.

BGC and the GWMG concur that a grid size of 200 feet by 200 feet allows modeling the changes in the mining area with sufficient accuracy, without having too many cells to make the model inefficient.

Impacts under the proposed action alternative would extend to Devils Canyon. However, the groundwater model does not have this small grid size at the groundwater discharge area along groundwater discharge areas like Devils Canyon. Thus, drawdowns in the vicinity of Devils Canyon are an estimate. Decreasing cell size near Devils Canyon could have improved model result accuracy, however, there is less information on groundwater levels and geology available in Devils Canyon than in the vicinity of the immediate mining area. Thus, decreasing cell size to the same size as in the mining area would have introduced additional uncertainties into the model, with respect to unknown groundwater heads and hydraulic parameters. A sensitivity analysis was used to estimate uncertainty and will be used to guide the extent of a monitoring and mitigation plan.

4.4. Model Layers

The groundwater model layering needs to represent the range in geologic characteristics of the site and the development of subsidence. One or more model layers should depict a single geologic unit, unless geologic units can be combined based on similar characteristics.

4.4.1. Selected Model Layers

In the groundwater model, the top of the top layer is defined by the ground surface, and the bottom of the bottom layer is in or at the upper boundary of the Pinal Schist at 3,400 feet below sea level. The model layers are horizontal, with varying thickness from 150 to 300 feet.

4.4.2. Rationale and Appropriateness

Anderson et al. (2015) state that “model layers should typically correspond to hydrostratigraphic units. However, if there are significant vertical head gradients, two or more layers should be used to represent a single hydrostratigraphic unit.” Because of significant dewatering from deep stratigraphic layers, significant vertical gradients are expected, and multiple layers must be used to represent single stratigraphic units.

BGC and the GWMG concur that the groundwater model layers are sufficient to represent the range in geologic characteristics of the project site and the development of subsidence. Relatively thin layers were used in the upper parts of the model where vertical hydraulic gradients are important to hydrogeologic conditions and potential impacts. The maximum depth of the mine workings is approximately 3,000 feet below sea level, a maximum depth for the model of 3,400 feet below sea level is adequate.

4.5. Time Frame for Model Runs

Mining and dewatering at the project area have been ongoing since 1910. Thus, current conditions are not at steady state, and cannot easily be used as starting conditions for a groundwater model estimating impacts from future project Operations. Stress periods need to match changes in model stresses, i.e., changes in dewatering or changes in model parameters caused by ore body removal or subsidence.

4.5.1. Selected Model Time Frame

The groundwater model uses pumping from 1910 through today for the transient model calibration and verification. The model was initially run for a predictive time period of 1,000 years, however, the GMWG decided that model results for greater than 200 years are highly speculative and not reasonable foreseeable. Thus, only results up to 200 years from the start of mine construction were included in the quantitative results presentation.

4.5.2. Rationale and Appropriateness

The model time frame is appropriate, if it can be used to answer the study objectives (Reilly and Harbaugh 2004). The model time frame must be long enough to show duration of the effect (Issue 6A-3).

BGC and the GWMG concur that the use of a steady state model for estimated pre-development conditions is an appropriate method for a qualitative calibration to pre-mining groundwater flow, because not enough data exists to allow for a quantitative calibration to pre-mining conditions. BGC and the GWMG also concur that the transient model using long-term mine dewatering rates and subsequent drops in groundwater heads can be used to calibrate the model to current conditions. Transient calibration is satisfactory to establish valid model parameters.

It should be noted that groundwater modeling predictions of more than a few hundred years are highly speculative, since no precise predictions regarding recharge can be made so far in the future.

4.6. Unsaturated Conditions

Baseline data collected indicate that unsaturated conditions generally occur near the ground surface in the Apache Leap Tuff in the mine area, with the water table approximately 100 to 400 feet below ground surface (Montgomery & Associates, 2017c). Additionally, dewatering of Shafts 9 and 10 has led to unsaturated conditions beneath the Whitetail Conglomerate, resulting in an unconfined aquifer in the Cretaceous volcanoclastic sediments inside the Resolution Graben (Montgomery & Associates, 2017c).

Several possibilities exist to simulate unsaturated conditions. The MODFLOW-SURFACT code effectively simulates unsaturated flow. The Pseudo Soil function, an unsaturated flow analog that allows for the model to run successfully by reducing unsaturated flow to a simplified step function rather than a nonlinear curve that is dependent on accurate estimation of unsaturated parameters. The Pseudo Soil function allows for numerical stability within the model and simplifies the system by allowing unsaturated model cells to freely drain, eliminating the unsaturated cells retaining residual water within pores. The Pseudo Soil function does not include a detailed simulation of unsaturated flow in the vadose zone, but rather is a simplification. BGC and the GWMG concur with the use of MODFLOW-SURFACT with the Pseudo Soil function to model unsaturated conditions.

Alternatively, the unsaturated flow zone (UZF) package (Niswonger et al., 2006) for MODFLOW could be used. The UZF package for MODFLOW was built as an alternative to codes that rely on the Richard's equation by using the method of characteristics to solve the kinematic wave equation for unsaturated flow. This is accomplished by neglecting the diffusive term in Richard's equation. When using MODFLOW-NWT, the UZF package requires the specification of vertical hydraulic conductivity for each layer. The UZF package uses the Brooks and Corey (1966) function to adjust saturated hydraulic conductivity as a function of soil moisture with a user-defined Brooks and Corey exponent.

4.6.1. Selected Model Package to Model Unsaturated Conditions

The model uses the MODFLOW-SURFACT Pseudo Soil function to model unsaturated conditions.

4.6.2. Rationale and Appropriateness

The UZF package cannot be used with MODFLOW-SURFACT; however, the greater efficiency of MODFLOW-SURFACT makes it preferable to use it over other versions of MODFLOW. BGC and the GWMG concur with the use of MODFLOW-SURFACT to model unsaturated conditions.

4.7. Hydraulic Parameters

Hydraulic properties for each model layer should initially be considered homogeneous, with anisotropy limited to structural features such as faulting and folding and to stratigraphic layering.

Further anisotropy may be added, based on model calibration needs. This includes introducing hydrostratigraphic zones within a given geologic layer or assigning anisotropy to the hydraulic conductivity tensor. Parameters in each zone must be reasonable for the geologic material considered, based on literature review, borehole logs and aquifer tests performed on the project site.

4.7.1. Selected Hydraulic Parameters

The groundwater model utilizes a range of possible values for each hydraulic parameter for each geologic layer based on aquifer testing. The stratigraphic and lithologic units have been translated in the model as different hydrogeologic units (HGU) zones of conductivity and are documented in "HGU Material Property Values" (WSP, 2018c).

The modeling process then refines the values during calibration. Each HGU was divided into individual zones, for which the modeled hydraulic conductivity values were adjusted separately within the field range to match observations, hence introducing heterogeneity into the system, however horizontal isotropy was maintained. To simulate the existing anisotropy in the Tal, a separate Tal zone along Devils Canyon was created that has a higher hydraulic conductivity that the surrounding zones of Tal (WSP, 2017, amended 2018). This zone of higher hydraulic conductivity promotes flow in the north-south direction in the Tal. The mine working and shafts have also been assigned unique hydrogeologic properties.

A part of the Whitetail Conglomerate (lowest portion) was modeled as anisotropic, with the vertical hydraulic conductivity one order of magnitude lower than the horizontal hydraulic conductivity. This allowed for improved simulation of the Whitetail Conglomerate as an aquitard and improved the calibration.

Calibrated hydraulic parameters (WSP 2017, and updated 2018c) fall within the range of measured parameters, except for hydraulic conductivity for Kvs. Calibrated hydraulic conductivity values for Kvs are lower than measured conductivities. Kvs is found only within the graben area underneath the Whitetail Conglomerate. Groundwater movement within Kvs is primarily through fractures. One pumping test (DHRES-01) performed in Kvs, resulted in a hydraulic conductivity range from 0.05 – 0.1 ft/day. For modeling purposes, Kvs was combined into one unit with underlying Quartz-rich sandstone, diorite, dacite porphyry, and quartz diorite. Calibrated hydraulic conductivities range from 0.001 – 0.008 ft/day. Head values in this unit are highly sensitive to the large drawdowns seen during dewatering and the model does a good job of replicating heads with the calibrated values, therefore, the calibrated hydraulic conductivities are justifiable (WSP 2017).

Additionally, the measured values are based on a single pump test that was performed in Kvs alone, and thus may not be representative for all of the Kvs.

Anisotropy in the Apache Leap Tuff was included by introducing a separate hydrostratigraphic zone within the geologic layer.

4.7.2. Rationale and Appropriateness

Reilly and Harbaugh (2004) recommends that explicit explanations for how parameter values are assigned to individual cells or areas. ASTM D5447-17 (2017) states that "Hydraulic property values are assigned in the model based upon geologic and aquifer testing data." BGC and the GWMG concur that hydraulic parameters assigned to individual hydrostratigraphic units are reasonable.

4.8. Boundary Conditions

Boundary conditions are applied at the edges of the model domain, and possibly to the internal domain. Three types of boundary conditions are considered, (1) specified head, (2) specified flux, and (3) head-dependent flux.

No-Flow: No-flow is a specified flux boundary condition for which no water is allowed to enter or exit the cell. No flow boundaries are placed along hydrogeologic divides and impermeable bedrock contacts. Delineating model boundaries at the edges of a watershed allows use of the no-flow boundary condition for topographically driven flow in the shallow aquifer system, assuming no regional flow system exists, and removes the need to define flux boundaries in these shallow aquifer systems.

Constant Heads/General Heads: Constant heads (CHD) are a specified head boundary condition and are applied to those cells for which where the head is known or specified. Prescribed constant heads can change for each stress period. Constant head cells are often used to describe lakes, rivers, streams, or to observed heads at a significant distance from the region of interest within the model domain.

Caution is noted when using a specified head boundary condition, since its value does not change, despite possible stresses to the system (e.g. a well pumping large volumes) and can inadvertently represent a nearly inexhaustible source or sink of water. Nor can a specified head change its value, if a large amount of areal flux is applied (i.e., recharge). For these situations, one must extend specified head boundary conditions well away from the region investigated in the model. In this way, boundary condition influence on the model objective is limited.

The general head boundary (GHB) package in MODFLOW-SURFACT simulates flow into/out of a cell based on a proportion of the head difference between the GHB cell and a MODFLOW-SURFACT computed head. High values of boundary conductivity, or large differences in head, force the GHB cell to act like a specified/constant head cell with no flow limit into/out of the model and should be monitored to ensure that fluxes are reasonable.

4.8.1. Selected Boundary Conditions along Western and Southern Boundary

The groundwater model utilizes no-flow boundaries along the western and southern boundaries of the Silver King Wash-Queen Creek watershed.

4.8.2. Rationale and Appropriateness

According to Anderson et al. (2015), no-flow boundaries may be defined along flow lines (hydraulic boundary). Hydraulic boundaries are not as permanent as physical boundaries, and the model boundary must be distant from the model stresses, so that the stresses simulated will not impact heads or fluxes near the hydraulic boundaries.

BGC and the GWMG concur that no-flow boundaries along the western and southern boundaries of the Silver King Wash-Queen Creek watersheds are appropriate. Groundwater flow is parallel to boundaries and does not cross boundaries.

4.8.3. Selected Boundary Conditions along Mineral Creek and Lyons Fork

The groundwater model utilizes general head boundaries along Mineral Creek and Lyons Fork forming the eastern boundary of the model.

4.8.4. Rationale and Appropriateness

BGC and the GWMG concur that general head boundaries along Mineral Creek and Lyons Fork is appropriate. Mineral Creek is a perennial creek, and thus is likely in connection with shallow groundwater. Lyons Fork is not a perennial creek; however, depth to water in the Lyons Fork may be estimated from shallow well HRES-10. According to Anderson et al. (2015), hydraulic boundaries may be defined from water table contours.

4.8.5. Selected Boundary Conditions along Northern Boundary

The groundwater model utilizes general head or no-flow boundaries along the northern boundary of the Lyons Fork watershed. Flows across the boundaries were evaluated during sensitivity analysis for the calibrated model, and were found to be small (WSP, 2018b). Change of the general head boundary to a no-flow boundary does not influence the calibration outcome.

4.8.6. Rationale and Appropriateness

According to Anderson et al. (2015), hydraulic boundaries may be defined from water table contours. ASTM D5609-64 (2015) emphasizes the need to evaluate boundaries as part of sensitivity testing and the verification and validation process for the model.

BGC and the GWMG concur that general head or no-flow boundaries are appropriate to use along the northern boundary. Boundary conditions were evaluated during sensitivity testing. This is a surface watershed boundary, and flow across the boundary is unlikely in the shallow aquifers. There is no information available regarding flow in the deeper aquifers. A general head boundary can be used in the deeper layers to evaluate flows across this boundary.

4.9. Groundwater – Surface Water Interaction

Groundwater - surface water interaction can be simulated in MODFLOW-SURFACT using the drains (DRN), or streamflow routing (SFR) packages. The SFR2 package allows for modeling of an unsaturated zone between stream and aquifer, while the SFR1 package assumes the stream is in contact with the aquifer.

The SFR2 is a head-dependent boundary condition that allows for the most complex stream routing, intermittent streams and stream diversions. In addition, the user has great flexibility on defining channel configurations from the relatively simple Manning's wide-channel assumption to rating curves describing depth and width. Flow into the stream is also based on the hydrologic gradient between the river stage and the groundwater system, as well as the connectedness between systems, as determined by a conductance term. The resultant hydraulic gradient between the stream and surrounding aquifer is highly dependent on properly characterizing stream elevations.

Drains in MODFLOW-SURFACT are a head-dependent boundary condition and are designed to remove water from the aquifer based on the difference between head in the aquifer and the drain's elevation. Flow into the drain (and out of the aquifer) occurs only when water levels in the aquifer are higher than the drain and is zero when heads drop below the drain elevation. Drains are commonly used to simulate springs or gaining reaches of streams in natural systems.

4.9.1. Modeling of Groundwater – Surface Water Interaction

The groundwater model uses drains to simulate springs and streams in the model area. Additionally, drains are used to simulate water removal from underground workings.

4.9.2. Rationale and Appropriateness

The SFR package allows for the most comprehensive modeling of groundwater-surface water interaction. The SRF package is not suited to model streamflow in response to short-term events like storms, but allows for modeling of changes in stream baseflow over time. Since most of the streams in the model area are ephemeral or intermittent streams, which flow only in response to rainfall events, the SFR package would not be applicable for those streams. Perennial reaches in Devils Canyon could be simulated with the SFR package.

BGC and the GWMG concur that drains are the adequate model tool to simulate all springs and most streams, as well as underground workings. Drains remove water from the aquifer, similar to actual springs and groundwater fed streams. ASTM D5447-17 (2017) describes drains as sinks within the aquifer system. Flow out of drains were compared to the water budget developed as part of the conceptual model.

Streams are a primary Forest resource to manage, and as such, the groundwater – surface water interaction is of large importance. Flow to drains or flow to stream cells in the SFR packages is highly dependent on the elevation of the drain or stream cell, as well as the conductivity of the drain or stream bed. Additionally, flow changes with changes in head. Accurate absolute values for heads are a prerequisite for correct drain or stream flow values. If the model calibration is lacking, and only relative changes in head can be evaluated, changes in stream or drain flow cannot be evaluated.

Due to the use of large grid cells and drains in the numerical model, flow to drains used to simulate stream cells could not be used to accurately model baseflow discharge to springs or perennial reaches. Changes in stream flow cannot be evaluated based on the groundwater model.

4.10. Initial Conditions

The initial head distribution across the model domain is required for all simulations. In numerical groundwater flow models, initial conditions consist of hydraulic heads specified for each model node at the beginning of the simulation. For steady state simulations, the choice of initial heads is not critical, except the closer the initial head distribution is to the steady state solution, then the faster the model will converge on a solution. It is also important to make sure the initial heads are all above the bottom of the cell to remove instability issues associated with wetting and drying of model cells. For steady state solutions, initial heads are generally placed at the top elevation of the model cells.

Initial conditions are important as a starting point for transient model calculations. Initial heads for the transient simulations should use modeled steady state head distributions. Steady state conditions are generally assumed to represent average conditions; such as mean water level for a long period of record.

4.10.1. Selected Initial Condition for Steady State Simulation

The initial head distribution in the groundwater model domain prior to mining in 1910 is not known. Therefore, an estimated steady state simulation was run to simulate reasonable head distributions for the time period before mining began.

4.10.2. Rationale and Appropriateness

Steady-state models do not require accurate initial conditions. For this reason, BGC and the GWMG concur the initial conditions are not critical to the accuracy of the model.

4.10.3. Selected Initial Condition for Transient Simulation

The heads from the steady state simulation were used to provide initial heads for the transient calibration simulation. The initial heads for the transient simulation are similar to the calibrated heads except where pumping was occurring.

4.10.4. Rationale and Appropriateness

ASTM D5610-94 (2014) requires defining steady-state initial conditions for a transient simulation. Even though the transient calibration period is sufficiently long (nearly 100 years) that slight differences in the initial conditions would have only minor effect on model calibration statistics, initial conditions for transient models should be specified as accurately as possible.

BGC and the GWMG concur that initial conditions for the transient runs must be created from the steady state simulation. The steady-state head distribution must be simulated by modeling hydrologic conditions, including boundary conditions. There are no actual data on water levels for 1910; however, groundwater heads can be evaluated qualitatively and compared to existing spring and stream elevations. The groundwater contour map for 1910 provided by WSP matches qualitative information regarding heads in the project area.

4.11. Groundwater Recharge

The main source of groundwater recharge is infiltration of precipitation. Recharge is a function of precipitation (magnitude, timing, intensity and nature of precipitation), slope and surface soil characteristics (which control the percentage of runoff versus infiltration), and vegetation (which influences evapotranspiration). Recharge is generally variably distributed.

4.11.1. Selected Recharge

Precipitation rates are derived from the PRISM (Parameter-elevation Relationships on Independent Slopes Model) model which spatially estimates precipitation into an interpolated digital elevation model of rainfall (Oregon State University, 2012). Precipitation rates were then verified with regional climate monitoring stations and weather stations in the vicinity of the project.

Due to a combination of poorly developed soils and vegetation, varying topography, and the short duration-high intensity precipitation in the region, the system is strongly runoff dominated (i.e., most precipitation ends up as runoff). In addition, any standing water or shallow soil moisture is mostly consumed by evapotranspiration, therefore local rates of recharge are low. Recharge to the shallow Apache Leap Tuff in the model area has also been studied and summarized by Woodhouse (1997).

Based on data from the PRISM stations within the model domain, two general precipitation zones were delineated - high elevation and low elevation. Prism data for each of these zones was averaged, and precipitation for each of these zones assumed constant at 22.7 inches per year for the high elevation/high precipitation zone, and 16.6 inches per year for the low elevation/low precipitation zone. Recharge derived from precipitation for each of these zones was based on rates estimated by Woodhouse (1997), and set to 4.1% for the high elevation zone, and 1.0% for the low elevation zone. Exceptions to the general high and low recharge zones, zones with outcropping geology that exhibit low hydraulic conductivity were set at the low end of recharge rates. Additionally, two enhanced recharge zones were defined alongside the two main drainages in the model – Queen Creek and Devils Canyon. These zones were conceptualized to concentrate runoff which would lead to higher infiltration rates for lower and higher elevation areas, respectively. Areal recharge was assumed to be steady state - no seasonal or long-term trends in recharge were simulated.

Recharge to the deep groundwater system is derived from a combination of downward flow through the Whitetail and potentially some recharge through the Paleozoic and Precambrian

Apache Group hydrogeologic units, where exposed along the Apache Leap escarpment and in Queen Creek Canyon, particularly during and following periods when Queen Creek is flowing.

Percent recharge from precipitation was estimated to account for water lost from canopy interception and evaporation, as well as evapotranspiration. Estimates of recharge percentages in the project area from the document “Perched Water in Fractured, Welded Tuff: Mechanism of Formation and Characteristics of Recharge” (Woodhouse, 1997), a study completed near the East Plant Site, was considered.

It should be noted that the potential area of mine subsidence has been assigned a high permeability and infiltration rate for mining and post-mining modeling scenarios, because the rock in the subsidence area fractures more and more and eventually becomes fully rubblized and allows for more infiltration.

4.11.2. Rationale and Appropriateness

According to Anderson et al. (2015), there are no universally applicable methods to estimate groundwater recharge. The recharge rate may be adjusted during calibrations.

BGC and the GWMG concur that the best available data was used to estimate recharge. Sensitivity analysis used a range of recharge rates to allow for changes in recharge rates due to changes in long term climatic changes.

4.12. Pumping Wells

MODFLOW-SURFACT’s well (WEL) package is designed to simulate wells which withdraw water from the aquifer (or add water to the aquifer) at a specified rate during a given stress period in which the rate is independent of the model cell area or head in the cell. Updated packages such as the Multi-node well (MNW2) package (Konikow et al., 2009) have improved on the earlier package to allow limitations on water withdrawal based on aquifer characteristics and screened elevation in the well and may be considered for modeling. Another possibility is the fracture well (FWL4) package. The fracture well is a form of specified flux boundary available in MODFLOW-SURFACT.

4.12.1. Selected Well Package

The model used the MODFLOW-SURFACT fracture well package to simulate water withdrawal from the aquifer, as well as water input into the aquifer.

4.12.2. Rationale and Appropriateness

ASTM D5447-17 (2017) describes wells as sinks within the aquifer system.

Dewatering has been going on for a long time and is an important part of the project activities. Resolution Copper has also been storing water in the west side of the Magma workings, which can be simulated as an injection well. BGC and the GWMG concur that the use of wells to simulate water withdrawal and input is an appropriate method and that flow in or out of wells should be determined, based on the water budget developed as part of the conceptual model.

4.13. Faults

Faults affect groundwater flow in a variety of ways and can cause potential hydrogeologic compartmentalization within the system. Faults can be simulated with the horizontal flow barrier (HFB) package (Hsieh and Freckleton, 1993), or by assigning separate hydraulic conductivities to the fault zone.

4.13.1. Selected Implementation of Faults

The groundwater model uses variations of hydraulic conductivities to simulate the effects of faulting on groundwater flows.

4.13.2. Rationale and Appropriateness

BGC and the GWMG concur that using separate hydrologic conductivities is appropriate to model faults. Faults may be conduits to flow as well as barriers. Using separate hydraulic conductivities gives flexibility in handling hydraulic characteristics faults in the model.

4.14. Special Considerations: Underground Workings

The model area contains underground workings of historic and existing mines. These workings were developed during the transient model calibration period and represent changes in hydraulic conductivities over time in the model domain.

4.14.1. Selected Implementation of Underground Workings

The groundwater model uses separate hydraulic conductivities to model underground workings, using the Time-varying Material Property (TMP) package in MODFLOW-SURFACT.

4.14.2. Rationale and Appropriateness

BGC and the GWMG concur that the TMP package is appropriate to model the underground workings. The existing continuing underground workings impact groundwater flow.

4.15. Groundwater Model Calibration

Calibration refers to adjusting model parameters to best match observed data. Calibration strategies can range from simple to complex. Hydraulic properties, as well as boundary conditions and stresses can be altered to reproduce simulated heads and fluxes that best match field measured values. Measured parameters, as well as expected ranges in parameter values, constrain how much adjustment of a calibration parameter is acceptable.

Calibration can be done in either steady state or transient simulations and is qualitatively assessed by matching observed and predicted contour maps of groundwater head. It is important that estimated flow paths are reproduced in the model. Quantitative assessment of calibration success is accomplished when the calibration targets are simulated within an acceptable level of error (ASTM, 2018). Uncertainty in the calibration target should also be considered, so that excessive effort is not expended in trying to perfectly match a target that is highly uncertain. Error is often evaluated using the scaled root mean-square error (rms error) method. The scaled rms error is equal to the ratio of the residual mean square error to the range of heads in the model. The scaled rms error equals the ratio of the residual mean square error to the range of heads in the model.

The rms error criterion for successful model calibration is limited to the average error in the model and can obscure portions of the model that are poorly predicted. It is preferred for model error to be randomly distributed across the domain and to not show any trends. If heads are consistently too high or too low in a region of the model, then parameters or boundary conditions may need to be adjusted, or eliminated, to remove the bias. If the source of error cannot be isolated, then additional field data collection may be necessary to improve conceptual understanding of the system being simulated.

Calibration can be achieved using manual trial and error by adjusting one parameter at a time or using sophisticated auto-calibration techniques (e.g. Doherty, 2005). While many different combinations of input parameters can produce similar output solutions (often termed non-unique), the verification process serves to justify model assumptions and predicted outcomes and to provide a measure of the confidence that might be placed in the model.

4.15.1. Performed Calibration

The groundwater model used a qualitative steady state calibration followed by a quantitative transient calibration using measured groundwater heads as targets. For the transient calibration the model was sub-divided into two time periods – pre-March 1998 and post-March 1998. Calibration was focused on the post-March 1998 period, to allow for shorter model runtimes and utilize the most reliable head measurements. Forty-seven targets with a total of 2805 observations were available for the shallow groundwater system, and 48 targets with a total of 2899 observations for the deep groundwater system. The groundwater heads in the shallow groundwater system ranged from 2211 feet amsl to 4434 feet amsl, while they ranged from 450 feet below msl to 3845 feet amsl in the deep groundwater system, giving a total range of observations of 4884 feet.

Calibration statistics show a residual mean of -9 feet, an absolute residual mean of 123 feet, and the scaled rms error error is 3.5%. The scaled rms error should be small (BLM 2008), and 3.5% is considered very good for a model of this extent.

Hydrographs comparing the simulated heads to observed heads were plotted for all targets (WSP 2017). The trends of the model hydrographs match the trends of the observed hydrographs reasonably well for the time period where calibration data are available. Actual simulated heads vary from observed heads from a few feet to several hundred feet. Modeled heads for wells closer to the proposed mine site show a better match to observed wells than heads for more distant wells. No data was made available comparing measured pre-1998 heads to modeled heads.

Transient fluxes were evaluated qualitatively. Fluxes into drains represent water discharged from groundwater into streams. They were not evaluated statistically but were qualitatively compared to measured flows.

4.15.2. Rationale and Appropriateness

The existing transient calibration was evaluated based on ASTM D5981/D5981M-18(2018). This standard explains that “calibration is a necessary, but not sufficient, condition which must be obtained to have confidence in the model’s predictions. Often, during calibration, it becomes apparent that there are no realistic values of the hydraulic properties of the soil or rock which will allow the model to reproduce the calibration targets. In these cases, the conceptual model of the site may need to be revisited or the construction of the model may need to be revised.”

Little data are available for pre-mining steady state conditions, and BGC and the GWMG concur that a quantitative calibration for steady state conditions is not feasible.

A calibration may not be unique, if several different calibrations may lead to the same result. The "uniqueness of the calibration" can be improved by either calibration to multiple hydrologic conditions or including groundwater flows as calibration targets.

Flows out of model drains were analyzed for the calibrated model. Simulated flows match estimates of baseflow recharge of perennial streams. This confirms that the calibration for the model is appropriate.

The groundwater model was calibrated with realistic hydraulic properties, therefore BGC and the GWMG concur that the calibration supports the model.

4.16. Water Balance

The water balance calculated by the groundwater model (WSP 2017) was compared to the estimated conceptual water budget (Montgomery & Associates, 2017a and 2018).

Montgomery & Associates (2017a) estimates that approximately 790 acre-feet per year of groundwater are discharged to surface water in the Queen Creek watershed (Superior Basin). The groundwater model predicts that 545 acre-feet per year of water are discharged to surface water (via drains and constant head cell) in the Queen Creek watershed. For Devils Canyon and Upper Mineral Creek, Montgomery & Associates (2018) estimate no groundwater contribution to surface water, however, baseflow analysis shows groundwater supported streams (Montgomery & Associates, 2017d). The groundwater model estimates 660 acre-feet per year of groundwater discharge to surface water for Devils Canyon and 560 acre-feet per year for the partial Mineral Creek watershed.

Montgomery & Associates (2018) estimate approximately 770 acre-feet per year of net recharge (recharge minus evapotranspiration) for the Queen Creek watershed, which matches the 710 acre-feet per year estimated by the groundwater model. For Devils Canyon, Montgomery & Associates (2018) estimate approximately 380 acre-feet per year of net recharge, while the groundwater model estimates approximately 1020 acre-feet per year. The discrepancy can be explained by the fact that Montgomery & Associates (2018) does not estimate groundwater discharge to surface water, but instead assumes groundwater lost to evapotranspiration. Estimating that 660 acre-feet per year of recharge goes to surface water discharge rather than to groundwater evapotranspiration, the net recharge estimated by the groundwater model would be

360 acre-feet per year, which compares well with the 380 acre-feet per year estimated by Montgomery & Associates (2018). The groundwater model does not include all of Upper Mineral Creek watershed, and thus a comparison cannot be made for Upper Mineral Creek watershed.

4.16.1. Rationale and Appropriateness

ASTM D5490 (2014) requires that the computed water balance for the groundwater model is compared to the measured or estimated values of a water budget.

The water balance calculated by the groundwater model shows values that are no more than 30% different than the estimated water budget. Numerically modeling a large, regional groundwater system includes a lot of assumptions and must by necessity include a lot of simplifications. Similarly, an estimated conceptual water budget also contains simplifications. Thus, a discrepancy of 30% between numerical and conceptual estimated water budget is realistic. Therefore, BGC and the GWMG concur that water balance calculated by the groundwater model is reasonable.

4.17. Predictive Simulations

The goal of the groundwater model is to serve as a tool for evaluating the potential impacts on surface and groundwater resources associated with the panel cave mining activities. Predictive simulations were used to model the impact of the mining development on water resources short–term at various stages during mining activities and long-term after reclamation.

The predictive simulations simulated two separate alternatives:

- The no action alternative: Under the no action alternative, de-watering continues from existing and already permitted infrastructure for 51 years; however, no panel cave mining takes place.
- The proposed action alternative: Under the proposed action alternative, de-watering is increased. Underground workings, the panel cave and associated subsidence was simulated using time-varying material property values for hydraulic conductivity, specific storage, and specific yield.

Under both alternatives, simulated dewatering ends after 51 years. The model was initially run for 1,000 years, however, for purposes of the EIS discussion, it was decided that model results for greater than 200 years are highly speculative, due to unknown potential changes in climate and precipitation. Thus, only results up to 200 years from the start of mine construction were presented quantitatively. Results of the model runs for up to 1000 years from the start of mine construction were discussed qualitatively.

4.17.1. Stress Periods

Stress periods were set up to simulate planned mine construction, operations, closure and reclamation and post-mining phases. Stress period length is one year during construction, six months during mine operations, and one year during mine closure and post-mining.

4.17.2. Initial Heads

The initial heads for the proposed action and no action alternative were obtained from the final heads in the calibrated model.

4.17.3. Time-Varying Material Properties

The initial material properties in the proposed action model were the same as those in the calibrated model but were then adjusted to model mining shafts, panel caving, and subsidence. The simulated changes were determined from the mine plans and geotechnical subsidence model results.

Mine shafts and tunnels were assigned a hydraulic conductivity of 100ft/day, the maximum conductivity possible, without making the model numerically unstable.

Under the no action alternative, only the deepening of one shaft required the use of time varying material properties.

Under the proposed action alternative, time varying properties were also necessary to model the panel cave and subsidence zone. In the panel cave and subsidence zone, hydraulic conductivity was assigned based on plastic strain data obtained from the subsidence geotechnical model (Itasca, 2017). The timing and magnitude of change in hydraulic conductivity applied to each cell was dependent on the timing and proximity to caving. Conductivity of each cell was increased over time from initial values to maximum values as the rock in each cell fractures more and more and eventually becomes a fully rubblized zone. Maximum hydraulic conductivity values were altered by a multiplier of 1E+6, to a maximum hydraulic conductivity of 100 ft/day.

Under the proposed action alternative, storage parameters (specific storage and specific yield) were also altered to account for increasing porosity and storage resulting from the fracturing and fragmentation (bulking) of the rock mass. Simulation of changing storage parameters was implemented in a similar fashion to hydraulic conductivity. The changes in rock volume over time was estimated from the subsidence geotechnical model and converted to changes in porosity, based on the swell factor simulated in the geotechnical model. The changes in porosity were represented in the model as changes in specific yield (Sy).

4.17.4. Recharge

Under the no action alternative, recharge remained the same as during calibration. Under the proposed action alternative, recharge was increased in the subsidence zone. Infiltration of precipitation is assumed to be increased in the subsidence zone. The increased recharge was implemented using a transient approach to mimic the propagation of the subsidence zone over time. The increased recharge was given a recharge rate of 4.39E-04 ft/day (1.9 inch/year), which is approximately 8.5% of mean annual precipitation. The recharge rate was chosen to correspond with the value used for enhanced recharge along streambeds within the Apache Leap Tuff.

4.17.5. Drains

Drain boundary conditions were used in the model to simulate the removal of water from the groundwater system due the mine dewatering. The features represented with drains are as follows:

- Underground workings
    - Historic Magma workings (in both proposed action and no action alternative)
    - Future workings during block cave development and production (in proposed action model only)
- Shafts 9 and 10 (in both proposed action and no action alternative)
- Shafts 11-14 (in proposed action model only)

All drain boundary conditions were removed for the closure and reclamation, and post closure model periods.

4.17.6. Results

4.17.6.1. Description of Results in EIS

Through the Groundwater Modeling Workgroup meetings, a consensus was reached regarding how the output of the groundwater models would be used and described in the EIS. Because groundwater models have uncertainty associated with their results, narrative descriptors of predicted impacts are used to divide impacts into three categories:

- Anticipated impacts
- Possible impacts
- Impacts not anticipated

Anticipated impacts occur where the predicted drawdown is larger or equal to 10 feet (for the no-action alternative), or where the predicted additional drawdown beyond the no-action alternative drawdown is larger or equal to 10 feet (for the action alternatives).

Possible impacts occur where the predicted drawdown from any sensitivity analysis is larger or equal to 10 feet (for the no-action alternative), or where the predicted additional drawdown from any sensitivity analysis beyond the no-action alternative drawdown is larger or equal to 10 feet (for the action alternatives).

Impacts are not anticipated where predicted drawdown from any sensitivity analysis is less than predicted 10 feet (for the no-action alternative), or the predicted additional drawdown beyond the no-action alternative drawdown is less than 10 feet (for the action alternatives).

For both the no-action and proposed action alternatives, figures in the report present the predicted 10-foot drawdown contour at 200 years after the start of mine operations. Predicted drawdown contours are shown for the base-case (i.e., best-calibrated) model, as well as being shown as one combined contour for all sensitivity analyses.

Additionally, predicted drawdowns and impacts are described in more detail with tables and figures in appendices for specific, sensitive locations and wells (Groundwater Dependent Ecosystems-GDEs).

4.17.6.2. Predictive Model Results for the No-Action Alternative

Under the no-action alternative, the Resolution Copper Mine would not be constructed. The model assumes that current dewatering of Shaft 9, 10 and the historical Magma workings would continue for 52 years (same duration as the mine life) and result in drawdown. The primary hydrogeologic units that experience drawdown from current dewatering are in the deep bedrock system including the Cretaceous volcaniclastic sediments (Kvs), Paleozoic (Pz) and younger Pre-Cambrian (pCy) HGUs. Most of the deep bedrock system is isolated from shallower groundwater, except south and west of the Apache Leap Tuff (Tal), where deeper units (Pz and pCy) outcrop at the ground surface. At the end of mine life, dewatering would create a predicted drawdown of over 500 feet centered around old Magma mine workings. No additional drawdown was predicted in the Apache Leap Tuff in the area of Shaft 9&10 (the primary location of dewatering) because the Whitetail Conglomerate (Tw) aquitard that underlies the Apache Leap Tuff impedes upward propagation of drawdown. West of the Apache Leap escarpment, predicted drawdown continues to propagate in the Pz and pCy HGUs with the 10-ft drawdown contour reaching Bored Spring and Hidden Spring. Within the Gila Conglomerate (QTg) the predicted 10-ft drawdown extends to Walker Spring.

After 52 years, dewatering of Shafts 9 and 10 and the Magma workings would be discontinued, allowing water levels to recover. At 200 years into the future, 148 years after dewatering ends, the predicted 10-ft drawdown contour continues to expand slightly further than it was simulated at the end of mine life period. After 200 years, predicted water levels will have rebounded over 500 feet around the old Magma mine workings (**Error! Reference source not found.**).

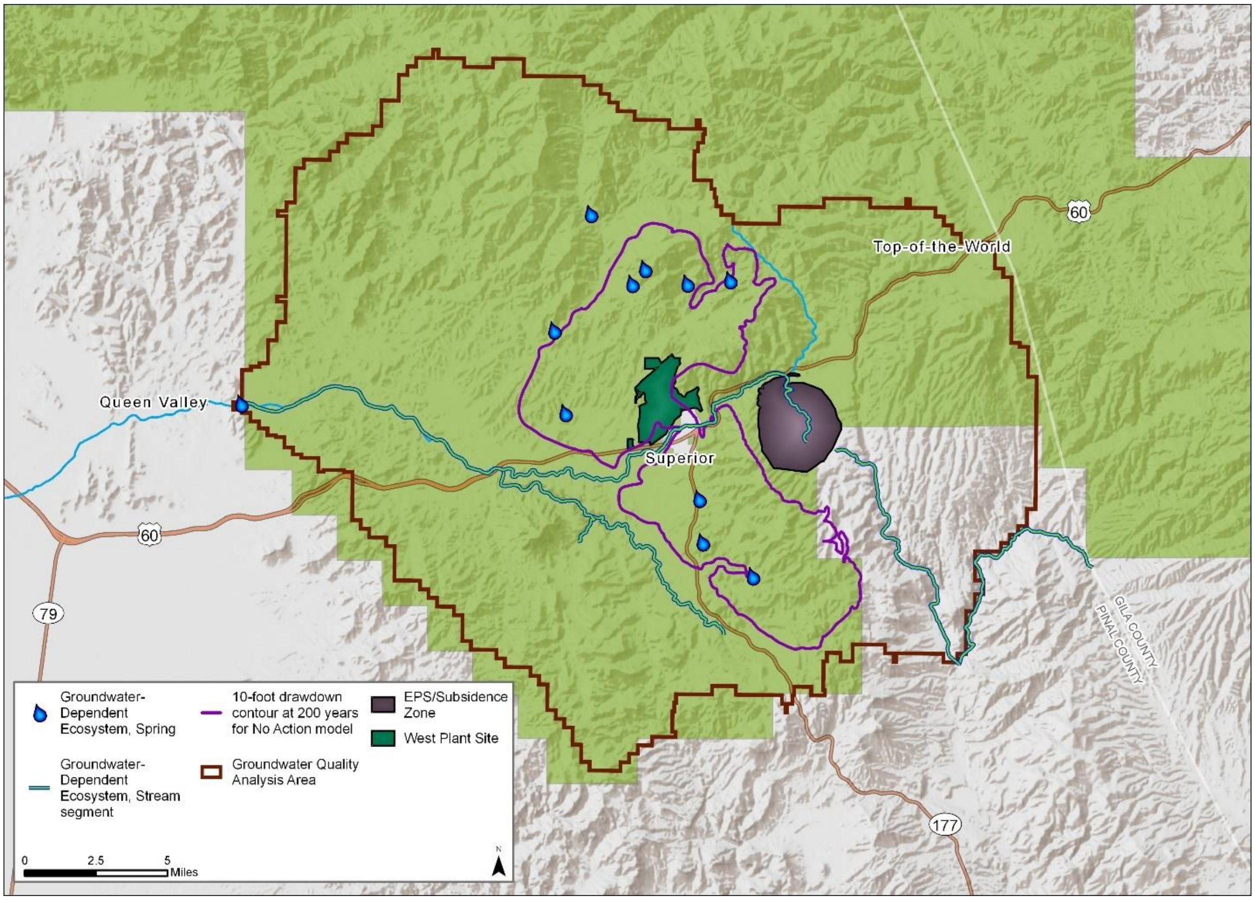

Figure 2. 10-Foot Drawdown Contour After 200 Years for No-Action Alternative

4.17.6.3. Predictive Model Results for the Action Alternatives

To safely mine during underground block caving activities, dewatering of the groundwater will be necessary in the underground mine, where the water will be collected in sumps and pumped out. Similar to the no-action alternative, dewatering ends after the end of the 52-year mine life period and water levels within the hydrogeologic system recover during the closure period.

At 200 years into the future, 148 years after dewatering ends, the predicted extent of the 10-foot drawdown zone had continued to increase, as water was predicted to continue to flow towards the block cave zone. The predicted 10-foot drawdown zone extends up to five miles from the East Plant Site. This predicted drawdown zone includes nine GDEs and water supply wells with predicted impacts exceeding 10 feet (**Error! Reference source not found.**) [Bitter, Bored, Hidden, McGinnel, McGinnel Mine, Walker, Kane, and DC-6.6W Springs, and well DHRES-16 representing wells in the Town of Superior]. However, six of these also had predicted drawdowns exceeding 10 ft under the No Action alternative. Hydrographs showing drawdowns for the GDEs indicate that the drawdown continues to increase after 200 years especially for GDEs to the south and the southeast of the East Plant Site. Detailed results are given in WSP (2018d).

The following is a key finding from the GWMG: *Predictions of drawdown are approximations of a complex physical system, inherently limited by the quality of input data and structural constraints imposed by the model grid and modeling approach. The groundwater model does not predict changes to flow magnitude and timing at a given GDE. By extension, drawdown contours do not represent the aerial extent of anticipated impacts to GDEs. These contours will be used to inform more site-specific impact monitoring and mitigation.*

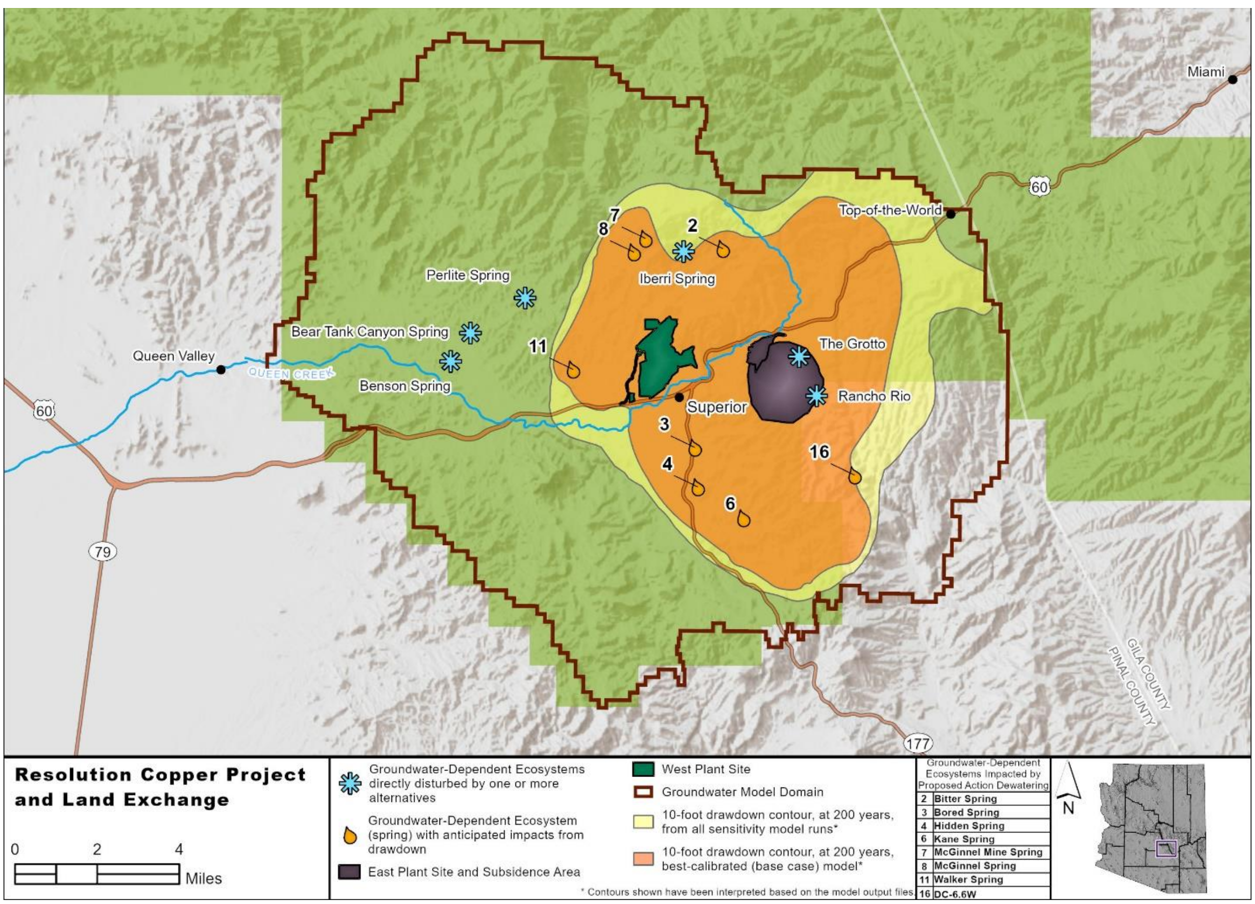

Figure 3. 10-Foot Drawdown Contour After 200 Years for Proposed Action Alternative

4.17.7. Rationale and Appropriateness of the Predictive Simulations

BGC and the GWMG concur that WSP set up predictive simulations according to the current mine plans, using best practices for groundwater modeling.

4.18. Sensitivity Analysis and Model Uncertainty

Sensitivity analysis is the process of changing one parameter in the model at a time and re-computing the error function. The purpose is two-fold. First, it can determine those parameters most sensitive to model output for use in the calibration process. Parameters that have the greatest impact on model output make better calibration parameters than those parameters less sensitive. Secondly, a sensitivity analysis allows some quantification of uncertainty in simulated response if parameters are adjusted over expected ranges.

Calibration sensitivity was evaluated for a broad range of parameters. The calibration sensitivity analysis showed that the model calibration is most sensitive to changes in hydraulic conductivities of the Apache Leap Tuff unit. This is expected as the Apache Leap Tuff controls most of the shallow groundwater flow in the eastern part of the model and contains a large amount of calibration targets. Additionally, the calibration is sensitive to changes in recharge rates which most affect the Apache Leap Tuff targets. Calibration sensitivity confirmed that the calibrated conductivity parameters resulted in the smallest residuals.

Sensitivity of the predicted results was evaluated for the following parameters:

- Hydraulic conductivity (Kx,Ky, Kz) of all zones within the Apache Leap Tuff (Tal)
- Hydraulic conductivity (Kx,Ky, Kz) of the Gila Conglomerate (QTg)
- Hydraulic conductivity (Kx,Ky, Kz) of the Lower Whitetail Conglomerate (Tw)
- Hydraulic conductivity (Kx,Ky, Kz) of the Paleozoic units (Pz) north and south of graben
- Hydraulic conductivity (Kx,Ky, Kz) of the Younger Precambrian unit (pCy) north of the graben
- Hydraulic conductivity (Kx,Ky, Kz) of the Precambrian Pinal Schist (pCpi)
- Hydraulic conductivity (Kx,Ky, Kz) of the Devils Canyon, JI Ranch and graben faults
- Recharge of high elevation zones
- Recharge of low elevation zones

- Specific yield of all zones within the Apache Leap Tuff
- Specific yield of the Paleozoic unit south of graben
- Specific yield of the Younger Precambrian unit south of graben
- Specific yield of block caved material (varied by +/- 25%, based on geomechanical model sensitivity range [ITASCA 2017]).
- Conversion of General Head Boundaries to No-Flow Boundaries.

Hydraulic conductivities were varied by one order of magnitude (factor of 10) in each direction and specific yield and recharge were varied by +/- 50%. For each sensitivity scenario, the historical model was run with the corresponding parameter change to ensure model calibration statistics were still acceptable and maintained a calibration error less than 10% Normalized Root Mean Squared Error (NRMS) value for the shallow and deep targets separately.

The results of the sensitivity analysis are given in WSP (2018e).

4.18.1. Rationale and Appropriateness of the Sensitivity Analysis

ASTM Guide D5611 (2016) covers techniques to conduct a sensitivity analysis for a groundwater flow model. The guide suggests that model inputs to be varied should be those that are likely to affect the computed hydraulic heads upon which the model's conclusions are based in the predictive simulations.

If, for some parameter that is being varied, the model's conclusions are changed but the change in calibration residuals is insignificant, then that parameter deserves special scrutiny. This case can invalidate model results because over the range of that parameter in which the model can be considered calibrated, the conclusions of the model change. Supporting documentation for the value of the parameter used in the prediction simulations is necessary (but not necessarily sufficient) to justify the conclusions of the model (ASTM D56112016).

In the sensitivity analysis performed by WSP (2018e), sufficient parameters were varied that BGC and the GWMG consider the sensitivity analysis complete. Many parameters maintain a valid model calibration when varied but create significant changes in the modeled drawdown and impacts. This signifies the uncertainty of the model results. Model results are presented with the sensitivity results to indicate the uncertainty bounds of the results.

BGC and the GWMG concur that WSP followed the guidelines of ASTM D5611 in performing the sensitivity analysis. Varying parameters create different drawdowns without impacting the calibration significantly. Ideally, under ASTM D5611, additional collection of data would allow determining those parameters with more certainty or collecting more calibration data in order to calibrate those parameters more closely. BGC and the GWMG concur, given the impracticality of collection additional calibration or parameter data, that displaying the results with the sensitivity analysis bounds for uncertainty is appropriate.

4.18.2. Modeling Uncertainty

Groundwater model results are influenced by uncertainty, due to the inability to define the exact temporal and spatial distribution of all parameter values and boundary conditions (Anderson et al. 2015). Additionally, uncertainty exists about the lithology, stratigraphy and structure in the model area. Uncertainty grows with the size of the model domain and is larger for large model domains. Uncertainty associated with estimates of aquifer parameters and boundary conditions must be evaluated (Anderson et al. 2015). Ranges for model parameter values based on testing or literature values show uncertainty in the parameters. The sensitivity analysis was used to establish the effect of uncertainty on the calibrated model.

It was determined that the uncertainty of the model was too large to give absolute heads or absolute fluxes. The change in heads relative to calibrated heads was determined to be the most reliable output upon which to base impact predictions.

Understanding and characterizing the uncertainties in the groundwater flow model was one of the primary charges of the GWMG. Appendix B contains a detailed description of the approach for addressing the uncertainties in the analysis.

4.19. Modeling Documentation

According to ASTM D5718-13, “Model documentation includes a written and graphical presentation of model assumptions and objectives, the conceptual model, code description, model construction, model calibration, predictive simulations, and conclusions. Model archival refers to a file or set of files (in both written and digital format) that contains logs of significant model simulations (that is, calibration, sensitivity and prediction simulations), supplemental calculations, model documentation, a copy of the model source code(s) or executable file(s) used, or both, and input and output data sets for significant model simulations.”

The Forest Service requested that Resolution Copper and their subcontractors take responsibility for properly archiving both the modeling files and software, in accordance with best practices as described in ASTM Standard D5718-13, Anderson et al. (2015), and USGS Report 2004-5038, so that the modeling can be recovered and reviewed in the future if necessary.

5.0 CONCURRENCE OF GROUNDWATER MODELING WORKGROUP

Ultimately, the final decision on how to approach the groundwater modeling analysis lies with the Tonto National Forest. By implementing a multi-agency, multi-disciplinary Groundwater Modeling Workgroup the NEPA team ensured that multiple and diverse professional viewpoints were brought into the groundwater modeling discussions for consideration by the Tonto National Forest. However, with such a diverse set of professionals, unanimous concurrence by the Groundwater Modeling Workgroup on all technical points was not necessarily an expected outcome.

This section summarizes technical points for which alternate or dissenting viewpoints were expressed by one or more members of the Groundwater Modeling Workgroup. The purpose of this section is to acknowledge these alternative viewpoints and provide a rationale for the differing approach taken by the Tonto National Forest.

5.1. Baseline conditions for modeling analysis

Appropriate baseline conditions for the modeling analysis was one of the first topics discussed by the Groundwater Modeling Workgroup, focused specifically on how the current groundwater pumping for dewatering would be accounted for in the model results. One member of the Groundwater Modeling Workgroup strongly advocated that the impacts disclosed in the EIS reflect all drawdown since dewatering pumping began in 2009, not just drawdown that would be caused by the block-cave mining.

Ultimately this question was viewed not as a technical modeling question, but rather a fundamental NEPA question. The decision by the Forest Service is clearly described in the Draft EIS (see “Key Decision on Use of Model Results – Baseline Conditions” section in the “Groundwater Quantity and Groundwater-Dependent Ecosystems” section in Chapter 3 of the Draft EIS), and the rationale is also contained in detail in the project record (Garrett 2018). The Forest Service made the decision that continued dewatering of the mine would be included as part of the no action alternative, and that the impacts resulting from the mine would be defined as the difference between the proposed action model and no action model.

Importantly, a second key part of the decision is that any observed effects of the past dewatering would be disclosed as ongoing trends as part of the affected environment, These are contained and analyzed in a section titled "Ongoing pumping and water level trends" in the "Groundwater Quantity and Groundwater-Dependent Ecosystems" section in Chapter 3 of the Draft EIS.

5.2. Strict use of 200-year timeframe

Most members of the Groundwater Modeling Workgroup acknowledged the substantial uncertainty involved with using any model at long time frames. Based on combined professional judgment within the Groundwater Modeling Workgroup, the time frame of 200 years (from start of mining) was selected by the Tonto National Forest as the period in which results could be reasonably quantified.

Few members of the Groundwater Modeling Workgroup disagreed with the premise that there is a reasonable limit to the quantification of modeling results. However, multiple members disagreed with a strict approach that no results should be discussed that take place past 200 years. These members argue that valuable non-quantitative information is still available from the groundwater mode after 200 years, including the trend of water levels, the time for water levels to reach equilibrium after completion of mining, and most importantly, whether the quantified results disclosed in the Draft EIS reflect the maximum impact expected, or whether drawdown would continue to get worse after 200 years.

The Tonto National Forest agreed with this dissenting viewpoint and in December 2018 modified the Draft EIS to discuss longer-term impacts (past 200 years) in qualitative terms. Five subsections were added to the Draft EIS to discuss longer-term effects under the No Action alternative, and longer-term effects due to the block-caving on springs, Devil's Canyon, Queen Creek, Telegraph Canyon, Arnett Creek, and water supply wells. These new qualitative discussions were based on longer-term modeled hydrographs disclosed during the Groundwater Modeling Workgroup in May 2018.

5.3. Revision of hydraulic properties – Kvs

Ideally, all hydraulic properties in the model would closely correlate with field measurements. Automated calibration routines can potentially skew the hydraulic properties of hydrogeologic units beyond the ranges actually observed in the field, and part of the modeler's task is to identify these discrepancies. In almost all cases, the ultimate calibrated values of hydraulic properties in the model fall within the range of values as measured in the field. One exception is the Cretaceous volcanoclastic unit (Kvs), which underlies the Whitetail Conglomerate and is part of the deeper aquifer system.

The calibrated values of hydraulic conductivity for the Kvs unit used in the model range from 0.008 to 0.001 ft/day, compared to field measurements from a 72-hour aquifer test on well DHRES-01 (0.05 to 0.1 ft/day) and from a 188-hour aquifer test on well DHRES-02 (0.1 to 0.6 ft/day). DHRES-01 is interpreted as being solely representative of the Kvs unit, while DHRES-02 is a combination of the Kvs and other Precambrian units. The DHRES-01 test involved only the pumping well, with no additional monitoring wells.

WSP noted this discrepancy in their report. Their reason for maintaining the calibrated values is that “as values in this unit are highly sensitive to the large drawdowns seen during dewatering and the model does a good job of replicating this … these modeled values are justifiable.” (WSP 2017).

The drawdown caused by the dewatering pumping is a much higher stress on the aquifer compared to individual pump tests and also closely replicates the same dewatering stresses that will occur throughout the mine life. It is critical that the model can adequately replicate the dewatering response. The Tonto National Forest concurred that given the limited comparison to one or two pump tests, the modeling choice was appropriate in order to ensure that dewatering drawdown was adequately replicated.

5.4. Revision of hydraulic properties – Vertical and horizontal hydraulic conductivity of Apache Leap Tuff and Whitetail Conglomerate, supported by review of borehole geophysical data/logs

One member of the workgroup identified a need to review borehole geophysical data or logs, and particularly acoustic televiewer logs, in order to analyze and understand anisotropy in the Apache Leap Tuff or Whitetail Conglomerate units. This issue was first raised during the Geology and Subsidence Modeling Workgroup meeting in April 2018 and was raised again in the context of the Groundwater Modeling Workgroup in July 2018. The suggestion was that these data should be reviewed in their original or processed forms by the workgroup and the results analyzed statistically. The suggestion was based on the premise that hydraulic conductivity properties in the Apache Leap Tuff and Whitetail Conglomerate units were modeled as equal in all dimensions (x,y and z). Meanwhile, as the workgroup member pointed out, some of the pump tests and visibly prominent jointing in the Apache Leap Tuff showed the potential for anisotropy .

In April 2018, the suggestion was provided to members of the Geology and Subsidence Modeling Workgroup. They did not believe the effort would provide new information beyond that already known. This same type of borehole information was already reviewed and interpreted by Resolution Copper geologists and incorporated into the overall geologic model, as noted in the geology report:

> "Oriented structural measurements from drill holes form a significant source of information. They are acquired either via down-hole oriented acoustic borehole image logs (ABI) and/or analysis of recovered core from most of the exploration holes drilled at Resolution since 2005. A total of 25,112 oriented geologic structures (including fault, joints, veins, folds, slickensides, stretching lineations) were available for use in the latest 2016 geo-structural interpretation." (4DGeo 2017)

The logging of thousands of structures is no minor task. The Geology and Subsidence Workgroup was charged with reviewing the quality assurance/quality control procedures of the Resolution Copper geologic data collection and interpretations and found them to be robust and reliable, and conducted by qualified specialists (BGC 2018b). There were no identified problems with Resolution Copper's data collection, processing, and use of these structural data; reworking the interpretations would provide no useful additional information._

Further, the premise on which the suggestion was based is not entirely correct.

> "All units, are modeled as isotropic in the horizontal direction (x and y), hence the range in values is due to heterogeneity (multiple zones per HGU). The Tal, which did show some anisotropy in test HRES-20 with hydraulic conductivity in the north-south direction greater than the east-west direction (as described in Section 3.2.4), was achieved by heterogeneity rather than anisotropy. Appendix B, shows the elongated zone 16 which was set as higher hydraulic conductivity allowing for the north-south response to be matched." (WSP 2019)

To include the anisotropic properties of the Apache Leap Tuff, different zones of Apache Leap Tuff were defined. The layout of these zones (long, narrow zones with different conductivities) introduce anisotropy on a larger scale, even if individual cells of the Apache Leap Tuff do not apply anisotropy. The Whitetail Conglomerate does not exhibit any horizontal anisotropy but does exhibit vertical anisotropy in the lowest unit.

In summary, the requested analysis was already conducted by Resolution Copper and the results incorporated into both the geologic model and the groundwater model, as reflected in the anisotropy in both the Apache Leap Tuff and Whitetail Conglomerate units. Having the NEPA team reanalyze the raw borehole geophysics data would duplicate high quality work already conducted by Resolution Copper and vetted by the Geology and Subsidence Workgroup while providing no substantial improvement in the groundwater model.

5.5. Independent collection of water quantity, quality or geologic data

One member of the Groundwater Modeling Workgroup advocated for the independent collection of additional baseline data directly by the Tonto National Forest, including both hydrologic (streamflow, groundwater levels, water quality), and geologic information.

The Tonto National Forest did not find that collection of additional data would be useful enough to the analysis to be warranted. As they currently stand, the data sets available to the Tonto National Forest for the NEPA analysis are robust—far more extensive than those typically available for many other projects. The period of record extends as far back as 2003 for many sampling locations, or almost 15 years of periodic or continual data collection, and includes groundwater data for multiple aquifers, extensive geologic drilling data, aquifer test data, surface water flow analysis, and groundwater and surface water quality sampling (including isotopes and radionuclides, alongside metals and general inorganic constituents).

A long period of record is one of the most desirable attributes of a hydrologic data set; such real-world measurements naturally have high variability, and a long period of record is one of the only methods by which such variation can be well understood. The collection of a handful of additional samples from the present time would not substantially improve the overall data set.

However, as with much of the data collection and analysis done by Resolution Copper, the Tonto National Forest still has the responsibility to properly vet the data and ensure that it was properly collected. As part of the NEPA analysis, the review of baseline data (particularly water quality and geologic data) included review of the quality assurance/quality control methods implemented by Resolution Copper and review of the results of QA/QC samples (duplicates, blanks, splits, etc.) The methods and quality controls employed by Resolution Copper were found to be adequate, consistent with industry standards, and sufficient to allow reliance on the hydrologic and geologic data sets.

After vetting, certain uncertainties still exist with the data sets. In particular, acknowledged uncertainties with the geologic data collected are documented in the results of the Geology and Subsidence Modeling Workgroup (BGC 2018b), and difficulties in translating surface water level measurements into flow values are discussed in various documents (BGC 2018a). The effect of these uncertainties are explicitly acknowledged and accounted for in the various analyses.

5.6. Choice of model and archiving of model

As discussed in Appendix A of this tech memo, both selection of an appropriate model platform and proper archiving of model files are clear requirements of pertinent industry guidance.

The selection of the MODFLOW-SURFACT model platform has been accepted by the Tonto National Forest as appropriate. While built on the open-source MODFLOW code (a clear industry standard), MODFLOW-SURFACE is a commercial version of the program and is not open-source. The commercial version is available to any users, but for purchase, not for free. The choice was found to be reasonable because MODFLOW-SURFACT has advantages that are particularly needed for the problem presented by the block-caving operation: it is more numerically stable when solving for groundwater flow in systems with steep hydraulic gradients and large differences in hydraulic conductivity across short distances, and it allows for time-varying hydraulic properties as caused by the block-caving.

Concerns were raised by a member of the Groundwater Modeling Workgroup that this choice contradicts modeling guidance, because Forest Service personnel would not be able to readily re-run the groundwater flow model in the future. After consideration, the Tonto National Forest took a different view, which was that the goal was to ensure that the model could be re-run in the future by qualified professionals, but not necessarily by Forest Service specialists. This decision essentially continues the division of work established by the Groundwater Modeling Workgroup, in which Resolution Copper and their contractors are responsible for the actual preparation and running of the models, but the Tonto National Forest with support and input from the Groundwater Modeling Workgroup is responsible for reviewing, vetting and accepting the model as appropriate.

On June 28, 2018 the Tonto National Forest requested that Resolution Copper commit to properly archiving both software and modeling runs as per industry guidance (Tonto National Forest 2018). The reply was received on October 9, 2018 stating: “Resolution Copper will ensure that groundwater modeling files and software will be archived appropriately.” (Resolution Copper 2018).

5.7. Direct modeling of groundwater/surface water interaction

When the Groundwater Modeling Workgroup first met in September 2017, most members of the group likely shared a common expectation that the groundwater flow model would explicitly predict changes in stream flows for key groundwater-dependent ecosystems, particularly Devil's Canyon. This is a common modeling approach, and there are several versions of streamflow packages available within MODFLOW that allow explicit modeling of the interaction between groundwater and surface water. Further, predicting any reductions in streamflow due to groundwater drawdown is the most fundamental hydrology question to be answered in the EIS.

Ultimately the groundwater flow model handles loss of water from the aquifer to the stream using a drain package and a series of drain cells, but otherwise does not explicitly model groundwater/surface water interaction. Further, the Tonto National Forest chose not to rely on any flow values derived from the drain cells in the analysis of impacts. The rationale for these decisions is explained elsewhere in this tech memo:

> "Streams are a primary Forest resource to manage, and as such, the groundwater – surface water interaction is of large importance. Flow to drains or flow to stream cells in the SFR packages is highly dependent on the elevation of the drain or stream cell, as well as the conductivity of the drain or stream bed. Additionally, flow changes with changes in head. Accurate absolute values for heads are a prerequisite for correct drain or stream flow values. If the model calibration is lacking, and only relative changes in head can be evaluated, changes in stream or drain flow cannot be evaluated." (Section 4.9 – "Groundwater – Surface Water Interaction")

> "Much effort was put into discussing the most appropriate model output upon which to rely. Possibilities requiring precise knowledge of absolute head were determined to be too uncertain to rely upon, as the calibration errors can be in the tens of feet at any given point, even when the overall groundwater model is considered well-calibrated. This ruled out reliance on any kind of flux changes from drain cells or from use of a streamflow package. In both cases, the cells turn on/off based on the absolute head. The relative drawdown (Proposed Action model minus No Action model) was determined to be the most reliable output upon which to base impact

> predictions, as any errors in absolute head would essentially cancel out." (Appendix A – "Process Step "G" – Uncertainty Analysis")

One member of the Groundwater Modeling Workgroup remained of the opinion that a full streamflow modeling package should have been used and the results reported in the DEIS, expressing concern about the:

> "model's lack of capability to simulate GW/SW interactions - The most important need the USFS has for the EIS analysis is the impact of the project on surface resources. The model here is not capable of modeling baseflow in Devil's Canyon and Queen Creek… This factor calls into question as to the whether the scope and capability of the model selected the subroutine packages invoked, and representation of the natural insitu system are adequately represented to the extent that should or could be based on reasonably known surface observations. USGS routinely creates MODFLOW models that include intricate surface water/groundwater interactions and result in calibrated surface water stream flow for output."

The concern stated is not a new one. This same concern has been central to the Groundwater Modeling Workgroup since the first meeting and has been discussed from numerous angles over a period of approximately 15 months. Importantly, nothing in the dissenting opinion provides a path forward that overcomes the fundamental problem: the known inaccuracy that would occur when using absolute head values, as is required by streamflow packages.

With respect to the U.S. Geological Survey (USGS), every modeling project is different. It is worth noting that on August 1, 2017, immediately prior to the start of the Groundwater Modeling Workgroup, the Tonto National Forest discussed the possibility of the USGS participating in the workgroup. The USGS declined involvement in the groundwater workgroup, in part because they felt that modeling of this particular system is so complex that it can't be modeled with any certainty (Tonto National Forest 2017).

The Groundwater Modeling Workgroup had this same concern in mind while reviewing the model and took great care not to attempt to model something that fundamentally can't be modeled, or to use the model in ways that imply unsupported precision or accuracy. The decision not to rely on flow values from the drain cell is one of the decisions made because of this concern; the chosen time frame for using quantitative results (200 years) and the chosen precision of results (no less than 10 feet) also reflect decisions made because of this concern. Another decision stemming directly from this concern is a requirement for operational monitoring for all locations potentially impacted, regardless of the model results.

In the end, the Tonto National Forest asserts that:

- A three-dimensional numerical finite-difference groundwater model is the only tool that can be reasonably used to predict the results of the block-caving and dewatering, given the complex geology, changes in geology and hydrology introduced by the block-caving, long time frames, and large geographic area.
- That tool has clear limitations. These limitations are represented in the decisions about how to use the model and what model output should be relied upon. This includes the decision to not explicitly model groundwater/surface water interaction with a streamflow package; this decision is an acknowledgment of a limitation of the model's ability to predict impacts.
- When fully considered, these acknowledged limitations do not prevent the model from providing a reasonable analysis of potential impacts for the purposes of the EIS.
- Operational monitoring of all potentially impacted groundwater-dependent ecosystems, regardless of groundwater model predictions of impact, provides a backstop to the acknowledged uncertainty of the groundwater model.

5.8. Reducing grid size near Devil's Canyon

The potential to reduce the spacing of the finite-difference element grid near Devil's Canyon and Mineral Creek was discussed during the workgroup meetings. The primary reason for reducing spacing in these areas would be to support explicit modeling of groundwater/surface water interaction, which is dependent on small changes in absolute head values. Finer grid spacing would allow more refinement to head values, and more refinement to flow impacts. As discussed in this section, explicit groundwater/surface water interaction was not modeled due to the potential error in absolute head values that occur even in a well-calibrated model. The current grid spacing is sufficient to support an analysis based on relative head change and the Tonto National Forest decided to maintain the existing grid spacing.

5.9. Basin water balance

The overall conceptual basin water balance was calculated by Resolution Copper (Montgomery & Associates 2018). The workgroup made multiple data requests of Resolution Copper in order to compare volumes or flows from the groundwater model to conceptual groundwater volumes or flows (WSP 2018a, 2018f, 2018g).

One member of the workgroup felt that one component of the overall basin water balance remained uncertain, the total discharge from the Queen Creek basin at Whitlow Ranch Dam, claiming incompatibility with USGS data: "I find it extremely unlikely that the USGS values and available water use data would result in cited basin discharge".

The available data are as follows:

- The gaging station upon which the water balance was based is a USGS gage (09478500).
- Baseflow was separated from runoff using two individual methods—hydrograph separation local minimum (HLM) and delta-filter (DF) (see figure 6, M&A Near West Conceptual Model).
- At the dam outlet, the bedrock geometry of the Apache Leap Tuff and Pinal Schist creates a natural constriction that forces groundwater from the floodplain alluvium to the surface.
- The calculated baseflow value from this gage for the period 2001-2017 was 1.43 cubic feet per second, which correlates to 1,035 acre-feet per year (Montgomery & Associates 2017b); this value was cited in a conceptual model report specific to the Near West tailings facility.
- The system wide water balance prepared to support the groundwater modeling effort estimates groundwater underflow at the basin outlet as 790 acre-feet per year (Montgomery & Associates 2018).

Contrary to the concerns expressed by this member of the workgroup, the basin discharge value used in the water balance work was based on USGS data, with separation analysis conducted to determine baseflow using two separate methods. This is a robust data source and a robust method of data processing. Further, the assumption that all floodplain groundwater flow exits the basin at this geologic pinch point is a reasonable one, particularly for a regional groundwater model. The Tonto National Forest found that the water balance work is sufficiently supported by real-world data.

5.10. Prediction of effects of land subsidence from individual well pumping

The Desert Wellfield model was not part of the Groundwater Modeling Workgroup review, since it is already a fully-vetted regulatory model from the Arizona Department of Water Resources (ADWR). However, one concern expressed by a member of the Groundwater Modeling Workgroup is worth mentioning here.

The Draft EIS and background documentation analyzes the potential for land subsidence to occur in the East Salt River Valley due to groundwater pumping. The analysis acknowledges that the subsidence has occurred in this geographic area and while groundwater levels have been recovering in the area, subsidence could continue to occur in the future if groundwater levels were to decline again.

The Draft EIS concludes: "Drawdown associated with the Desert Wellfield would contribute to lowering of groundwater levels in the basin, including near two known areas of known ground subsidence. Further detailed analysis of land subsidence resulting from groundwater withdrawal is not feasible beyond noting the potential for any pumping to contribute to drawdown and subsidence. Subsidence effects are a basin-wide phenomenon, and the impact from one individual pumping source cannot be predicted or quantified."

One member noted that this approach was unacceptable and requested analysis of subsidence impacts with and without project pumping.

While the basic physical mechanisms of land subsidence are reasonably well understood, to the knowledge of the Tonto National Forest and the NEPA team, no analytical techniques exist that would allow an incremental amount of pumping and related drawdown to be quantitatively tied to an incremental amount of land subsidence across the East Salt River Valley. The disclosure of the potential for project pumping to contribute to land subsidence is reasonable; however, quantification of that potential is simply not feasible. If such techniques are identified during public comment and review, an alternative approach would be considered by the Tonto National Forest.

6.0 CLOSURE

We trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

BGC ENGINEERING USA INC.
per:

(Name), (credentials)
(Title/position)

(Name), (credentials)
(Title/position)

Reviewed by:

(Name), (credentials)
(Title/position)

PM/TR/cr/admin

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WSP USA, 2018f. Technical Memo - Resolution Copper Groundwater Flow Model – Predicted Flows to Block Cave. September 28, 2018

WSP USA, 2018g. Technical Memo - Resolution Copper Groundwater Flow Model – Watershed Water Balance. October 2018

WSP USA. 2019. Resolution Copper Groundwater Flow Model Report. February 15.

APPENDIX A
Participants of the Groundwater Modeling Workgroup

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APPENDIX B
Adherence of Groundwater Modeling Process to Professional Standards (SWCA Memo)

For the most part, the reference documents consulted describe a similar overall modeling process, as detailed in table 1.1. The "Process Step Reference ID" is an arbitrary designation solely for the purpose of organizing this attachment.

Table 1.1 – Generalized process steps for groundwater modeling, based on reference documents

Process Step Reference ID	Process Step	Anderson, Woessner & Hunt	ASTM Standards	USGS Scientific Investigations Report 2004-5038	Nevada BLM
A	Define the purpose of the model/study objectives	Chapter 2	D5447-17, Sec. 6.2		
B	Construct a conceptual model	Chapter 2	D5447-17, Sec. 6.3		3.2
C	Select the mathematical model and code	Chapter 3	D5447-17, Sec. 6.4	p. 1-4	3.3
D	Translate the conceptual model into a numerical model:	Chapters 4-7	D5447-17, Sec. 6.5		
D1	Determine dimensionality (1D, 2D, 3D)	Chapter 4	D5447-17, Sec 6.5.1		
D2	Select boundary conditions	Chapter 4	D5447-17, Sec. 6.5.5 D5609-16	p. 16-17	
D3	Determine grid spacing, layers, and assign material parameters	Chapter 5	D5447-17, Sec. 6.5.3 (grid spacing) D5447-17, Sec. 6.5.7 (parameters)	p. 5-10 (grid spacing) p. 10-15 (parameters)	
D4	Identify sources and sinks	Chapter 6			
D5	Determine steady-state or transient simulation, and time steps	Chapter 7	D5447-17, Sec 6.5.2 D5447-17, Sec. 6.5.4	p. 15-16 (time steps)	
D6	Define initial conditions	Chapter 7	D5447-17, Sec 6.5.6	p. 17-20	

Process Step Reference ID	Process Step	Anderson, Woessner & Hunt	ASTM Standards	USGS Scientific Investigations Report 2004-5038	Nevada BLM
			D5610-94 (2014)		
E	Calibration and sensitivity analysis	Chapter 9	D5447-17, Sec 6.6 (calibration) D5447-17, Sec 6.7 (sensitivity) D5981/D5981M-18 (calibration) D5611-94 (2016) (sensitivity) D5490-93 (2014) (comparing model to site-specific information)	p. 23-24	3.4, 3.5, 3.6
F	Predictive modeling runs	Chapter 10	D5447-17, Sec. 6.8		3.7
G	Uncertainty analysis	Chapter 10			
H	Model documentation and archiving	Chapter 11	D5447-17, Sec. 7 D5718-13	p. 24-26	5.0
I	Postaudit		D5447-17, Sec. 6.9		

Blank cells indicate no specific mention of this process step in the reference document

Each process step defined in table 1.1 is explored in more detail below.

Process Step "A" - Define the Purpose of the Model/Study Objectives

The purpose of the model and the study objectives are clearly spelled out in WSP 2018, Section 1.5 "Purpose of the Model and Structure of the Report".

Process Step "B" - Construct a Conceptual Model

The conceptual model is described in detail in WSP 2018, Section 2.2 "Hydrogeologic Conceptual Model". Considerations suggested in reference documents to incorporate into development of the conceptual model are listed in table 1.2.

Table 1.2. Conceptual model considerations (process step "B")

Consideration	Reference	Addressed in:
Boundaries	Anderson et al Sec 2.3.1	Boundaries are not discussed as part of the conceptual model (WSP 2018, Sec 2), but are discussed as a concept as part of the numerical model construction (WSP 2018, Sec 3.1.6)
Geologic framework	Anderson et al Sec 2.3.2; ASTM D5447-17, Sec. 6.3.1.1	The general geologic framework is discussed in WSP 2018, Sec 2.2.1, and the specific effect of faults on groundwater flow is further discussed in WSP 2018, Sec 2.2.5. In addition, the overall geologic framework was investigated by the NEPA team through the Geology/Subsidence Working Group; the results of this group are contained in the project record [see PR #0110927, "DRAFT Resolution Copper Project and Land Exchange Environmental Impact Statement: Geologic Data and Subsidence Modeling Evaluation Report, November 30, 2018"].
Hydrologic framework and media type	Anderson et al Sec 2.3.2; ASTM D5447-17, Sec. 6.3.1.2	WSP 2018, Sec 2.2.2
Hydraulic properties	D5447-17, Sec 6.3.1.3	WSP 2018, Sec 2.2.3
Flow Direction and Source and sinks	Anderson et al Sec 2.3.3; D5447-17, Sec. 6.3.1.4	WSP 2018, Sec 2.2.4
Groundwater Budget	Anderson et al Sec 2.3.4	The groundwater budget was explored during the Groundwater Modeling Workgroup meetings, and documented in several reports including: Montgomery & Associates. "System - wide Hydrologic Water Flow Budget", June 6, 2018 WSP. "Resolution Copper Groundwater Flow Model - Watershed Water Balance", October 10, 2018 WSP. "Resolution Copper Groundwater Flow Model – Predicted Flows to Block Cave", September 28, 2018
Analysis of data deficiencies and potential sources of error	Anderson et al Sec. 2.4; D5447-17, Sec 6.3.2	Discussion of data deficiencies and potential sources of error was a primary topic of

Consideration	Reference	Addressed in:
with the conceptual model		discussion by the Groundwater Modeling Workgroup.

Process Step "C" - Select the Mathematical Model and Code

Selection of the mathematical code for the model is discussed in WSP 2018, Sec. 3.1.2. In addition, the Groundwater Modeling Workgroup specifically discussed the use of MODFLOW-SURFACT as the selected code because of the need to incorporate time-varying aquifer properties due to the block-cave zone.

Process Step "D1" – Create Numerical Model (Dimensionality)

The selection of a three-dimensional model (versus a two- or one-dimensional model) was not explicitly discussed by the modelers or by the Groundwater Modeling Workgroup, but given the complexity of the system was understood to be necessary. That said, the potential to describe impacts to the system in ways not involving a three-dimensional numerical groundwater flow model was a continued point of discussion by the Groundwater Modeling Workgroup.

Process Step "D2" – Create Numerical Model (Select Boundary Conditions)

Development of boundary conditions in the numerical model is described in detail in WSP 2018, Section 3.1.6 "Boundary Conditions". Considerations suggested in reference documents to incorporate into development of the boundary conditions are listed in table 1.3.

Table 1.3. Boundary condition considerations (process step "D2")

Consideration	Reference	Addressed in:
Identify physical boundaries of the flow system	D5609-16, Sec 6.2; Anderson et al Sec 4.2.1, 4.2.2	WSP 2018 Sec. 3.1.6
Formulate mathematical representation of the boundaries	D5609-16, Sec 6.3; Anderson et al Sec 4.2.3	WSP 2018 Sec. 3.1.6
Conduct sensitivity testing of boundary conditions (head-dependent) when system is under stress	D5609-16, Sec 6.4 D5447-17, Sec. 6.5.5	This topic was raised specifically during the Groundwater Modeling Workgroup. Specific data were requested and provided to assess changes in the boundary during calibration runs (provided 1/9/18, Item #1) and predictive runs

		(discussed during 6/19/18 meeting, represented by sensitivity run A-43).

Process Step "D3" – Create Numerical Model (Grid, Layers, Material Parameters)

Development of the numerical model structure (grid spacing, layers) and the material parameters is described in WSP 2018 Section 3.1.3 "Model Domain", Section 3.1.4 "Model Grid and Layers", and Section 3.1.8 "Material Properties". Considerations suggested in reference documents to incorporate into development of the boundary conditions are listed in table 1.4.

Table 1.4. Grid, layer, and material property considerations (process step "D3")

Consideration	Reference	Addressed in:
Locate nodes as close as possible to pumping wells	D5447-17, Sec. 6.5.3	The primary pumping from the model occurs from the mine itself; the discussion of centering the closely spaced grid around this area is in WSP 2018 Sec 3.1.4
Locate model edges and hydrologic boundaries accurately	D5447-17, Sec. 6.5.3	Not explicitly discussed
Avoid large contrasts in adjacent nodal spacings	D5447-17, Sec. 6.5.3	WSP 2018 Sec 3.1.4
Hydraulic conductivity	Anderson et al Sec 5.4.1.1	WSP 2018 Sec 3.1.8 ("Hydraulic Conductivity" subsection). This section also gives special consideration to the effect of faults and mine workings on hydraulic parameters. Post-calibration changes in hydraulic conductivity are discussed in WSP 2018 Sec 3.2.5 ("Hydraulic Conductivity" and "Faults" subsections). Hydraulic conductivity values used in the Life of Mine model and Closure/Post-Closure models are discussed in WSP 2018 Sec 4.1.5 and 4.2.3, with a focus on changes within the block-cave zone.
Storage	Anderson et al Sec 5.4.1.2	WSP 2018 Sec 3.1.8 ("Storativity" subsection). This section also gives special consideration to the effect of faults and mine workings on hydraulic parameters. Post-calibration changes in storativity are discussed in WSP 2018 Sec 3.2.5 ("Storage" subsection). Storage values

Consideration	Reference	Addressed in:
		used in the Life of Mine model and Closure/Post-Closure models are discussed in WSP 2018 Sec 4.1.5 and 4.2.3, with a focus on changes within the block-cave zone.
Vertical leakance, resistance, and conductance	Anderson et al Sec 5.4.1.3	Post-calibration vertical anisotropy is discussed in WSP 2018 Sec 3.2.5 ("Hydraulic Conductivity" subsection)
Total porosity and effective porosity	Anderson et al Sec 5.4.1.4	Not explicitly discussed. As noted in Anderson et al, typically porosity is a concern for particle tracking, but is superceded by empirically-derived storativity in most flow modeling.
Recharge	Anderson et al Sec 5.4.2.1	WSP 2018 Sec 3.1.6 ("Areal Recharge" subsection). Recharge used in the Life of Mine model and Closure/Post-Closure models are discussed in WSP 2018 Sec 4.1.6 and 4.2.4.
Pumping Rates	Anderson et al Sec 5.4.2.2	WSP 2018 Sec 1.3.2; 3.1.6 ("Fractured Well" subsection). Pumping (via drain cells) used in the Life of Mine model and Closure/Post-Closure models are discussed in WSP 2018 Sec 4.1.7 and 4.2.5.
Evapotranspiration	Anderson et al Sec 5.4.2.3	WSP 2018 Sec. 3.1.6 ("Drains" subsection). The modeling choice to use a combination of drains to simulate evapotranspiration and areal recharge to simulate surface flow infiltration was also a key discussion point of the Groundwater Modeling Workgroup, including the ability to predict flow losses using drain cells, the preference for drain/recharge cells over the MODFLOW streamflow package, and the accuracy of the drain/recharge cells with respect to the water budget. Specific documentation includes: Data provided 1/9/18, Items #2, #5, and #8 Data provided 2/13/18, Item #2, #5 Montgomery & Associates. "System - wide Hydrologic Water Flow Budget", June 6, 2018 WSP. "Resolution Copper Groundwater Flow Model - Watershed Water Balance", October 10, 2018

Process Step "D4" – Create Numerical Model (Sources and sinks)

The WSP modeling report handles sources and sinks as part of the boundary conditions, which are addressed primarily in WSP 2018 Sec. 3.1.6 "Boundary Conditions". Considerations suggested in reference documents to incorporate into development of source/sinks in the model are listed in table 1.5.

Table 1.5. Source and sink considerations (process step "D4")

Consideration	Reference	Addressed in:
Pumping and Injection Wells	Anderson et al Sec 6.2	See table 1.4 "Pumping Rates"
Areally distributed source and sinks (recharge and evapotranspiration)	Anderson et al Sec 6.3	See table 1.4 "Evapotranspiration" and "Recharge"
Drains and springs; Streams; Wetlands	Anderson et al Sec 6.4, 6.5, and 6.7	See table 1.4 "Pumping Rates" and "Evapotranspiration". Discussions of the Groundwater Modeling Workgroup included the modeling choice to model spring flow (within channels), stream discharge, and evapotranspiration from riparian vegetation and wetlands into drain cells along major drainages. Other springs and associated wetlands not along major drainages were not modeled as substantial points of discharge.
Lakes	Anderson et al Sec 6.6	No lakes existed in the model area and were not explicitly modeled.

Process Step "D5" – Create Numerical Model (Determine Steady-state, Transient, and Time Steps)

Discussion of the choice of time periods and time steps is included in WSP 2018 for the Historical transient model (WSP 2018, Sec 3.1.5), the Life of Mine transient model (WSP 2018, Sec 4.1.3) and the Closure/Post-Closure transient model (WSP 2018, Sec 4.2.1).

Process Step "D6" – Create Numerical Model (Define initial conditions)

A variety of initial conditions are used in the modeling process. A steady-state stress period was used to replicate water levels in 1910 (no measured data exist from that time). These were then used in the historical transient model intended to replicate conditions from 1910-2016; the portion of this transient model from 1998 to 2016 was used in calibration to ensure a well-calibrated model for use in the predictive runs (Life of Mine, Closure/Post-Closure transient models). As part of this, the final head distribution in the calibrated historical model becomes the initial conditions input into the predictive model runs.

Selection of initial conditions is discussed for the historical transient model (WSP 2018 Sec 3.1.5 "Time Discretization" and Sec 3.1.7 "Initial Conditions"), the Life of Mine model (WSP 2018 Sec 4.1.3 "Time Discretization" and Sec 4.1.4 "Initial Heads"), and the Closure/Post-Closure model (WSP 2018 Sec 4.2.1 "Time Discretization" and Sec 4.2.2 "Initial Heads").

Process Step "E" – Calibration and Sensitivity Analyses

Discussion of both calibration and sensitivity analyses are discussed in detail in WSP 2018 Section 3.2 "Model Calibration". The steps identified as part of the calibration are shown in table 1.6.

Table 1.6. Calibration steps and considerations (process step "E")

Consideration	Reference	Addressed in:
Establish Calibration Targets	D5981M-18 Sec 6	WSP 3.2.2 "Calibration Targets"
Identify Calibration Parameters	D5981M-18 Sec 7	WSP 3.2.5 "Calibrated Hydraulic Parameters". Calibration parameters included hydraulic conductivity, storage, and fault conductivity.
History Matching; Manual Calibration; Automated Calibration	D5981M-18 Sec 8 – 10	WSP 3.2.1 "Calibration Approach" and 3.2.4 "Calibration Results". Note that both manual and automated calibration techniques were used, as described in WSP 3.2.1. The output produced to analyze and document the calibration is discussed in the next item.
Data Comparisons	D5490-93 (2014)	D5490-93 (2014) identifies a variety of ways to analyze output. These include: Potentiometric Head Residuals [WSP 2018 Sec 3.2.4 "Hydrographs"] Residual Statistics [WSP 2018 Sec 3.2.4 "Target Statistics"]

Consideration	Reference	Addressed in:
		Correlation Among Residuals [WSP 2018 Sec 3.2.4 "Scatterplots"] Flow-Related Residuals [WSP 2018 Sec 3.2.1 notes that flow-related values were used as calibration targets, but only qualitatively]
Sensitivity Analyses	D5611-94 (2016)	WSP 2018 Sec 3.2.6 "Parameters Sensitivity"

It should be noted that the ASTM guidance on sensitivity analysis (D5611-94 (2016)) includes one step that was not conducted in the Resolution groundwater modeling process: determining the type of sensitivity (Type I – Type IV). However, other guidance (Anderson et al, Sections 9.4.2 and 9.5.3) does not follow this scheme.

Process Step "F" – Predictive Runs

Predictive runs are discussed in detail in WSP 2018 Sec. 4 "Predictive Models", including both the Life of Mine model and the Closure/Post-Closure model.

One key note in guidance (ASTM D5447-17) notes that during predictive runs, boundary conditions should be checked to ensure that stresses applied during the predictive runs does not greatly change boundary fluxes. This documentation was requested and provided during the Groundwater Modeling Workgroup (see table 1.3).

Process Step "G" – Uncertainty Analysis

Understanding and characterizing the uncertainties in the groundwater flow model was one of the primary charges of the Groundwater Modeling Workgroup. The workgroup ultimately selected an approach for addressing the uncertainties in the analysis.

1. Conduct a wide variety of sensitivity modeling runs (approximately 44 in total). These include:
    a. Sensitivity runs meant to vary model input parameters within reasonable bounds, to test the effect on model calibration and outcomes. A total of 26 runs were conducted varying hydraulic conductivities, primarily associated with fault zones, a total of 13 runs were conducted varying storage parameters, and a total of 2 runs were conducted varying recharge parameters.
    b. Sensitivity runs meant to test boundary conditions (1 run).
    c. Sensitivity runs meant to test conditions in the block cave zone (1 run).
    d. Sensitivity runs meant to inform climate change discussions (1 run).

2. Much effort was put into discussing the most appropriate model output upon which to rely. Possibilities requiring precise knowledge of absolute head were determined to be too uncertain to rely upon, as the calibration errors can be in the tens of feet at any given point, even when the overall groundwater model is considered well-calibrated. This ruled out reliance on any kind of flux changes from drain cells or from use of a streamflow package. In both cases, the cells turn on/off based on the absolute head. The relative drawdown (Proposed Action model minus No Action model) was determined to be the most reliable output upon which to base impact predictions, as any errors in absolute head would essentially cancel out.

3. Much effort was put into determining the appropriate precision of modeling results, considering the uncertainties inherent in the model. Ultimately, the Groundwater Modeling Workgroup selected 10 feet as the limit of precision. The Groundwater Modeling Workgroup also discussed the appropriate time period considering the uncertainties inherent in modeling long time periods, and chose to restrict output to 200 years after mine closure.

4. Based on this decision, the 10-foot contour was used to identify areas of “anticipated” impact from the groundwater model, with output provided as spatial contours, and as hydrographs at each specific sensitive receptor location. However, recognizing the uncertainties inherent in the modeling, the base case 10-foot contours was supplemented with the 10-foot contour encompassing all sensitivity runs. Any sensitive receptors within this area were also considered to have potential anticipated impacts.

5. With respect to sensitive receptors—specifically termed Groundwater Dependent Ecosystems (GDEs)—any identified GDEs were assumed to be in connection with the regional aquifer unless site-specific evidence suggested otherwise.

6. Finally, the Groundwater Modeling Workgroup recognized that the uncertainties inherent in the model limited its use as a tool to analyze smaller changes in groundwater level (less than 10 feet) that could still have substantial impacts on GDEs. To address this uncertainty, the Groundwater Modeling Workgroup envisions real-world monitoring of GDEs during operations in order to identify any changes, even if not anticipated by the groundwater model.

Process Step “H” – Model Documentation and Archiving

On June 28, 2018, the Forest Service requested that Resolution Copper and their subcontractors take responsibility for properly archiving both the modeling files and software, in accordance with best practices as described in Anderson, Woessner & Hunt, ASTM Standard D5718-13, and USGS Report 2004-5038, so that the modeling can be recovered and reviewed in the future if necessary. In order to document this step for the project record, the Forest Service requested written confirmation that Resolution Copper will ensure that all groundwater modeling files and software will be archived in accordance with appropriate standards.

On October 9, 2018, Resolution Copper responded in writing that to confirm that groundwater modeling files and software would be archived appropriately.

Process Step "I" – Post-Audit

As noted in the guidance, post-audits are generally performed several years after submittal of the modeling report, upon receipt of real-world monitoring data. This would be beyond the purview of the modeling analysis for the DEIS.