NEVADA DIVISION OF
ENVIRONMENTAL PROTECTION

Bureau of Mining Regulation and Reclamation

GUIDANCE DOCUMENT

HYDROGEOLOGIC GROUNDWATER FLOW MODELING AT MINE SITES

1. Introduction

Mining operations in the State of Nevada commonly interact with local and regional groundwater, due to groundwater pumping for dewatering, groundwater rebound, pit-lake formation, infiltration of excess water, and various other processes. The complexity of these interactions often necessitates the use of groundwater flow models to predict future conditions quantitatively, and the Nevada Division of Environmental Protection, Bureau of Mining Regulation and Reclamation (Division) may require groundwater models during permitting actions. This guidance document summarizes the background and general requirements for groundwater flow modeling studies submitted to the Division. This guidance is not intended to include all possible requirements and may need periodic updates as scientific understanding and groundwater modeling methods evolve. The guidance document provides a reference for Division employees, mining operators and consultants, and other users/reviewers of groundwater flow models, and is intended to decrease the number of technical comments associated with groundwater models, thereby increasing permitting efficiency and decreasing permitting time.

In its most basic definition, a model is a simplification of a physical system. A groundwater flow model specifically is a simplification of the groundwater system of interest and is meant to be used for a specific purpose (United States Bureau of Land Management [BLM], 2008; Reilly and Harbaugh, 2004). When required by the Division, groundwater flow models are intended to be used to assess possible future impacts to the waters of the State, as regulated in the Nevada Administrative Code (NAC) 445A.424 and 445A.429.

Not every mining operation is required to conduct groundwater modeling, because not all mining operations have the potential to impact waters of the State. Examples of mining operations not typically required to perform groundwater modeling include small-scale placer operations and mines not interacting with groundwater (i.e., no degradation, pumping, infiltration, pit lakes, etc.), or where more simple data analyses suffice. However, other regulatory agencies including the Nevada Division of Water Resources (NDWR), the United States Forest Service (USFS), and the BLM may have other permitting requirements. Mine operators are encouraged to contact all applicable agencies for their regulatory requirements. All groundwater models for regulated mining operations should be submitted to the Division for review.

Site-specific Division requirements for groundwater flow modeling, if any, for mining operations already holding a water pollution control permit (WPCP) are commonly described in the WPCP. Whether required specifically by the WPCP or otherwise by the Division, all groundwater flow models submitted to the Division must adhere to general requirements set forth herein. This guidance is not intended to be overly prescriptive, however, as to the exact content, layout, and design of groundwater flow modeling and model reports. Not every process discussed in this document will be applicable at every site, and additional processes may warrant investigation at specific sites. This guidance is not meant to stifle innovation with respect to the methods and analyses utilized in groundwater modeling. Instead the guidance is designed to provide a reference and to describe documentation that is required for submitted groundwater models.

The goal of groundwater modeling submitted to the Division is to provide a tool that can be used to inform policy and permitting decisions made by the Division. The results of these models may play a significant role in assessing future impacts of proposed mine sites. Because of the weight carried by these groundwater models and their inherent uncertainty, preparers of groundwater models have a duty to evaluate and communicate the objectives and uncertainties of the model, as well as possible alternative actions to reduce environmental impacts, in associated correspondence and reports (Bredehoeft, 2005; Reilly and Harbaugh, 2004; Oreskes et al., 1994). Additionally, reviewers of groundwater models have the duty to provide fair and reasonable reviews based on best scientific practices. Alternatives included in model reports could include mitigation measures or other such actions. Analysis of alternatives in this sense is different from requirements for alternatives analysis considered in National Environmental Policy Act (NEPA) documents. In this case, alternative actions can be identified and evaluated during the operation of the project and be instituted when required, instead of relying on a previous NEPA analysis completed during initial permitting.

Useful summaries of the numerous complexities involved in groundwater flow modeling and model reporting are provided in Anderson et al. (2015), Barnett et al. (2012), BLM (2008), Bredehoeft (2003 and 2005), Reilly and Harbaugh (2004). Groundwater modeling guidance papers distributed by the National Groundwater Association (NGWA) may be found at the NGWA website NGWA Modeling Guidance and various ASTM International documents. Modelers should be keenly aware of common modeling errors, such as those summarized at the conclusion of each chapter of Anderson et al. (2015). These listings of common errors should prove especially useful, as the Division has encountered many of these errors in submitted groundwater model reports.

2. Groundwater Modeling Methods

There are various types of groundwater flow models, and each type has associated input data, assumed parameters, and model outputs. One major distinction amongst types of groundwater models is analytical models versus numerical models. In general, analytical solutions are simpler to solve, are continuous in time and space, and require less input data. In contrast, numerical models are more complex and solve the governing equations of groundwater flow for discrete points in space and in time (Anderson et al., 2015). The majority of groundwater flow models provided to the Division are numerical models. Numerical models may not always be the appropriate modeling method, however; in some cases, more simple methods may provide more useful results (Kelson et al., 2002; Shevenell, 2000). Aryafar et al. (2007) provides a review of analytical methods in reference to calculating groundwater inflow to pit lakes and Hunt et al. (2003) discuss various methodologies for simulating lake-groundwater interactions. In addition to true analytical methods, the analytic element method is effective in many instances and should be considered for mining applications. See Hunt (2006) and Strack (2003) for additional information on analytic element methods. Groundwater modelers should consider carefully the most appropriate modeling method and describe the reasoning for the applied method in model reports (Reilly and Harbaugh, 2004). An important consideration in choosing the modeling method is what questions the groundwater model must answer (e.g., impact to stream baseflow, the water balance of a pit lake, potential for pit-lake discharge to the downgradient aquifer, etc.). In many cases there are numerous questions asked of a groundwater model. The questions asked, and the required resolution of the answers, should be primary considerations when choosing the modeling method (Kelson et al., 2002). The reasoning behind these choices and what questions the model is attempting to answer must be outlined in the modeling report.

Much of the guidance summarized in this document is applicable to both analytical and numerical models, but, owing to their greater complexity, numerical models are emphasized. Numerical modeling may be

further subdivided into finite-element and finite-difference methods. The differences between these methods are beyond the scope of this document, but comparisons between both methods indicate that similar results are obtained regardless of the numerical method (Anderson et al., 2015). The Division accepts either numerical method.

Numerous proprietary (e.g., owned by a particular company and not open for public use and review) and open-source groundwater modeling codes exist for both finite-difference and finite-element methods. In the experience of the Division, the most widely used groundwater modeling code is MODFLOW (Harbaugh, 2005), or variations of this code including MODFLOW-USG (Panday et al., 2015) and MODFLOW SURFACT (HGL, 2002). MODFLOW and its variations are finite-difference codes originally developed by the United States Geological Survey (USGS). MODFLOW is ideal for a variety of reasons including it is open-source and freely available with instruction manuals, it has been subject to considerable internal review, and it has been utilized in numerous peer-reviewed scientific research articles. Aside from MODFLOW, the Division has experience with other codes, both proprietary and open-source. Until now, no official guidance has been offered by the Division on the use of proprietary versus open-source codes.

It is the belief of the Division that proprietary codes are not appropriate for use in predictive models impacting regulatory decisions and public or environmental health, for a variety of reasons (Nordstrom, 2012). This is not to say that some proprietary codes do not sufficiently solve groundwater flow problems (e.g., Trefry and Muffels, 2007); however, the lack of transparency is an issue. If the modeler wishes to use a proprietary code, or an open-source code having undocumented performance, an assessment must be made as to the reliability of the code. Although Oreskes et al. (1994) question the term "verification" for numerical codes, the Division believes reproducibility must be assessed and confirmed. There are various documents relating to the testing and assurance of reliability of modeling codes (ASTM D6025-96; van der Heijde, 1996; van der Heijde and Kanzer, 1997). Reporting of code testing should be consistent with these documents. Once a specific code has been tested, and the testing has been approved by the Division, the code need not be tested again by future users, unless the code has subsequently been modified. The Division will maintain a listing of tested codes on its website here BMRR Guidance Documents Additionally, an operational copy and instruction manual of any proprietary code must be supplied to the Division for use in model review. The requirement for modeling to use publicly available codes is consistent with actions taken by other states; for example, see requirements for groundwater models submitted to the California Department of Water Resources (CDWR, 2016).

Owing to the relative simplicity and variability of programming languages used in analytical models, analytical modeling codes must be specified, but need not be verified. Any analytical modeling code used in groundwater flow modeling must be submitted concurrent with the model report in which it has been applied.

3. Conceptual Models

Prior to any analytical or numerical modeling, the region to be simulated must be simplified in order to characterize the hydrogeologic framework and define pertinent processes that must be quantitatively incorporated into the subsequent modeling procedures. This simplification process is referred to as conceptual model creation. The conceptual model is primarily a qualitative representation of the system of interest and includes information on physiographic, geologic, climatologic, hydrologic, and geochemical characteristics (Anderson et al., 2015). Conceptual models could include some quantitative information or analysis, which help to understand the system. Although conceptual models may quickly mature, the process should be iterative and upon additional data collection conceptual and numerical

models may need to be changed (ASTM D5979-96; Bredehoeft, 2005). Conceptual models are one of the most important parts of the groundwater model, although they are sometimes overlooked. The iterative processes of conceptual and numerical modeling should be used to guide additional data collection, which will lead to a more advanced understanding of the groundwater system. Additionally, comparison of multiple conceptual models with observations is an excellent way to test assumptions about processes occurring at the site of interest (Bredehoeft, 2003; 2005).

It is critical that the conceptual model for the hydrogeologic system of interest be a reasonable approximation of the system. Conceptual models should adhere to the principle of parsimony (also known as Occam's Razor); that is, the conceptual model should be the simplest possible description of the system while including all relevant processes and containing enough complexity to represent important system behavior. This concept requires that all relevant features or processes reasonably expected to occur in the model domain are included in the conceptual model. It is also imperative for all processes included in the conceptual model to be included in the numerical model, and vice versa. Finally, the conceptual model must be built upon and supported by abundant and representative site-specific characterization data. Where minor data gaps exist, which is common for groundwater modeling, appropriate substitutions may be made. The model report must address these data gaps and provide supporting reasoning for any substitutions. The Division may require additional data collection to fill data gaps in a specified timeframe.

Important aspects of the conceptual model include geologic and hydrogeologic framework, sources of groundwater recharge and discharge, groundwater flow directions, hydrogeologic discontinuities, boundary conditions, climatologic characteristics, groundwater budget components, structural geologic framework, and geochemical characteristics. The conceptual model for the site of interest should be compared to any applicable published conceptual models and water budgets (e.g., Heilweil and Brooks, 2011), and any differences addressed. An in-depth discussion of the aspects and importance of conceptual model formation is provided in Anderson et al. (2015), ASTM D5979-96, and Bredehoeft (2003; 2005). Additionally, Maurer et al. (2004) and Heilweil and Brooks (2011) provide useful references for the creation of conceptual models that are specific to Nevada.

4. Data Collection and Model Integration

In the experience of the Division, it is common for modeling exercises to reach advanced stages without adequate characterization data, which are required per NAC 445A.395 for surface water and groundwater quality, and NAC 445A.396 for overburden, waste rock, and ore, although not all of these attributes are applicable to groundwater modeling. In the case of groundwater modeling, adequate characterization data would include information on the hydrologic characteristics of the simulated area.

Hydrologic or related data gaps commonly appearing in submissions to the Division include hydraulic parameters, subsurface lithologic relationships, climatic conditions, and information on geochemical attributes. When modeling proceeds with these critical data gaps unaccounted for, the resulting model predictions may not be applicable to the project and may require revision. This issue is a common cause of delays in permitting decisions. The source of many attributes of importance for groundwater flow models is aquifer testing (e.g., slug tests, pumping tests, etc.). Although these tests are not the subject of the modeling report, they are very important in the review of the model as hydraulic parameters are commonly one of the most uncertain aspects of a groundwater model. All values used for hydraulic parameters, and an explanation of how they were derived, must be reported. If specific aquifer testing was done for the modeling, supporting documentation must be included as appendices or as references to previously submitted reports.

One of the main aspects of data collection that should be considered during construction of the conceptual and numerical models is spatial variability. It is common for variables such as hydraulic parameters and concentrations of geochemical constituents to vary across a site, and from one lithologic unit to another. Additionally, temporal variability should be considered where appropriate (e.g., for climatic or geochemical variations). There are a variety of methods useful for statistical analysis of these types of variability (ITRC, 2013). The groundwater model report and supporting documentation must include appropriate characterization data and must demonstrate that these characterization data are inclusive of the variability observed on the site or reasonably expected to occur in the subsurface or through time. For example, the hydraulic properties of a hydrogeologic unit could not reasonably be assumed to be adequately represented by values obtained in localized testing of one borehole. In this example, the representativeness of the hydraulic parameters would need to be tested in a number of other boreholes on the site, which would either demonstrate the lack of variability, or set bounds for the model parameter.

The determination of adequacy of characterization data will be made by the Division based on best scientific and engineering judgement. The amount of characterization data required is not consistent across all sites, and more complex sites or sites having a greater potential to degrade waters of the State will require additional characterization. Finally, it is important for all data integrated in groundwater models to use consistent measurement systems (e.g., datums, units, etc.). All groundwater models must be completed using data in the North American Vertical Datum of 1988 (NAVD88). Horizontal spatial coordinates must be in Universal Transverse Mercator (UTM) Zone 11 with units of meters.

5. Boundary Conditions, Hydraulic Properties, and Model Discretization

Although each component of the model has importance for the subsequent groundwater modeling, assigning the type and location of boundaries to the model domain requires special attention. In the experience of the Division it is common for modelers to assign model domains that are too restrictive (i.e., with respect to size), such that the stresses induced in the model during the simulation propagate to the model boundary. These transient changes in the hydraulic conditions along the boundary likely affect the simulated conditions throughout the interior of the model, calling model predictions into question. Common examples observed by the Division are cones of depression due to dewatering or pit-lake evaporation that intersect the model boundaries. Models with this or similar traits will not be accepted by the Division unless appropriate evidence is provided that the boundary effects do not impact simulations. Modelers are directed to Anderson et al. (2015) for important considerations on appropriate physical or hydrologic features for setting model boundaries.

Around the perimeter (and the upper and lower extents) of a groundwater flow model, the hydrologic conditions set by the modeler are known as the boundary conditions. These boundary conditions are one of the key driving factors in the simulation of groundwater dynamics in response to stresses imposed by mining. There are generally three mathematical classes of boundary conditions: specified head boundaries (Dirichlet conditions), specified flow boundaries (Neumann conditions), and head-dependent boundaries (Cauchy conditions). The implementation of these different boundaries in numerical models is beyond the scope of this document, but modelers are strongly encouraged to consult Anderson et al. (2015), ASTM D5447-04, BLM (2008), and Reilly and Harbaugh (2004) during the assignment of boundary conditions. Additionally, the USGS has produced numerous studies summarizing regional models and assessments within Nevada that contain useful estimates of boundary conditions and other applicable quantities (Belcher and Sweetkind, 2010; Berger, 2000; Brooks et al., 2014; Handman and Kilroy, 1997; Heilweil and Brooks, 2011; Maurer et al., 1996; 2004; Plume, 2009). Modelers must be cognizant of the potential for boundary conditions to overly constrain model results. In this case the simulations may produce

reasonable comparisons to observations under previous stresses but may not be well suited to evaluating future stresses on the system, which may be of greater magnitude.

The influence of climate (precipitation, evaporation, etc.) over the surface of the model domain constitutes another important boundary condition. Climate is one of the main controlling factors in groundwater flow, primarily through recharge, derived from precipitation, and discharge through evaporation and evapotranspiration (ET). There are a variety of methods for the implementation of these boundaries. Useful references for the representation of climatic boundaries in groundwater models for Nevada include Heilweil and Brooks (2011) and Brooks et al. (2014). In specific reference to recharge estimates, many groundwater modeling studies utilize the Maxey-Eakin method (Maxey and Eakin, 1949) to estimate basin-wide recharge. While this method has been utilized previously in groundwater budgets for Nevada (Avon and Durbin, 1994; Stone et al., 2001), it is important that all datasets utilized be internally consistent and applicable to the method (Berger et al., 2008). Although the Maxey-Eakin method is generally of use for recharge estimation, modelers should be aware that a variety of other methods could provide useful estimates (Sanford, 2002; Scanlon et al., 2002).

The most important consideration for the Division in reference to climate is that the climatic input values used in the groundwater model are representative of the site. A common error in groundwater models reviewed by the Division is the assignment of critical parameters (e.g., ET rate, ET extinction depth, precipitation rate) based on empirical datasets from localities drastically different from the project site in question. These differences could include aspect, elevation, latitude, and other variables, which have been demonstrated to control the values of climatic attributes in Nevada (Jeton et al., 2006; Shevenell, 1999). Therefore, groundwater models must utilize site-specific data for climatic inputs near to the mine site, and appropriate regional datasets for the remainder of the modeled region. If site-specific data are not available, they should be collected, unless the Division approves the use of a reasonable proxy, and a thorough discussion of the possible effects of that substitution is included. Examples of tools that may be appropriate for substituting for site-specific climatic information are the *Climate Engine* (Huntington et al., 2017) online application and the formulations provided by Shevenell (1999).

Because pit lakes are commonly the focus of groundwater models submitted to the Division, open-water evaporation rates from predicted pit lakes should be carefully assessed. The most common method for obtaining open-water evaporation rates converts pan evaporation using a scalar, generally assigned a value of approximately 0.7 (Eichinger et al., 2003). Although this does account for the tendency for pan-evaporation rates to over-estimate evaporation (Eichinger et al., 2003), the scalars are commonly not based on any empirical evidence specific to the site. In fact, detailed modeling and evaporation measurements indicate that scalars to relate pan evaporation to pit-lake evaporation change seasonally (McJannet et al., 2017). The American Society of Civil Engineers (ASCE) has formulated a standard method for calculating reference evapotranspiration (ET; ASCE, 2005), which is utilized in the calculations of *Climate Engine* (Huntington et al., 2017). Reference evapotranspiration is likely not applicable to pit-lake surfaces, however, as the method was designed to calculate evapotranspiration from a vegetated surface (ASCE, 2005). Therefore pit-lake evaporation calculations may require more advanced methods (e.g., Finch and Calver, 2008; McJannet et al., 2017), or be based on some site-specific information.

In addition to regional climatic effects, the water budget of a groundwater system is also controlled by transient and localized recharge and discharge processes. Examples of localized recharge processes include focused recharge at stream channels (for losing streams), return flow from irrigation, and focused recharge due to rapid infiltration basins (RIBs). Localized discharge processes could include ET from phreatophytes, pumping wells (for mine dewatering and other groundwater pumping), and discharge to

streams (for gaining streams). Each of these processes may vary spatially and through time in the groundwater model domain.

Of the quantities assigned to the hydrogeologic units during model creation, the hydraulic properties are some of the most uncertain and most important in governing final predictions. Hydraulic properties assigned to hydrogeologic units include hydraulic conductivity (K), transmissivity (T), specific yield (S_y), specific storage (S_s), and porosity. Of these parameters, models are commonly most sensitive to K values (or the closely related T); this dependence is further complicated by the variation of K values over several orders of magnitude (Maurer et al., 2004). Storativity values (e.g., S_y, S_s) may be important in transient model simulations, however the range in storativity parameters is commonly small compared to that of K values; see Anderson et al. (2015) Table 5.1 for example. Porosity, specifically the effective porosity, can be an important parameter in solute-transport simulations; see the discussion in Section 7 below. These hydraulic parameters may be determined by a number of methods including aquifer tests and borehole geophysical methods (ASTM 5979-96; Fetter, 2001; Freeze and Cherry, 1979; Keys, 1990). Groundwater models must assess the uncertainty in the assignment of hydraulic property values using either sensitivity analyses or other methods, as discussed below.

Another consideration related to the representation of the hydrogeologic framework in numerical models is the discretization of both the model domain (i.e., the cell or element size) and the time period simulated in the model. Each important hydrogeologic unit identified by the conceptual model must be incorporated into the discretized model domain. Information on the surface exposure and subsurface relationships among hydrogeologic units is generally derived from geologic maps, borehole logs, geophysical surveys, and other methods (ASTM 5979-96). Once the distribution of hydrogeologic units is determined, those hydrogeologic units must be adequately discretized in the model domain. The size of model units (either cells or elements in finite-difference and finite-element codes, respectively) must be fine enough to capture continuity relationships observed in the field, such as observed fault structures or other continuous hydrogeologic units. When model units are too coarse, hydrogeologic continuity may be unrealistically disrupted. Spatial discretization and representing system continuity are especially important when simulating lake-groundwater interactions, as described by Hunt et al. (2003). Likewise, the temporal discretization must be fine enough such that stresses simulated in the model are realistically incorporated. See Reilly and Harbaugh (2004) for examples of discretization concerns. Various methods can be used to quantify the suitability of the model discretization to the problem at hand. The grid Peclet number and Courant number are examples that are applied to solute transport simulations (Barnett et al., 2012), and in the case of solute transport simulations these quantities must always be reported, as well as any applicable convergence criteria.

6. Model Calibration

Once the hydrogeologic framework for the model domain and simulated time are discretized, hydraulic parameters and boundary conditions are assigned, and simulated stresses are incorporated into the groundwater model, the code is then executed and simulated hydraulic conditions (e.g., hydraulic head, fluxes, etc.) are output. Before using the simulated conditions for any decision making, the degree to which these simulated hydraulic conditions agree with observations must be assessed. Following the assessment, boundary conditions and/or hydraulic parameters are commonly changed to achieve a greater degree of agreement between model predictions and observations. Any changes must be realistic, however, and cannot be made simply to improve model performance. These combined processes of assessment and refinement are generally referred to as model calibration.

Model calibration is an iterative process and may require re-conceptualization of the groundwater flow system in the area of interest (Reilly and Harbaugh, 2004). This process of iteration between conceptual model and calibration may result in a more realistic, reliable, and useful groundwater flow model (Bredehoeft, 2005).

The overall purpose of the calibration process is not only to attain a greater degree of agreement with observations, but also to facilitate an understanding of the sensitivity of the results to different input parameters (ASTM D5981-96), and an understanding of the spatial variability of uncertainty throughout the model domain (Reilly and Harbaugh, 2004). There are a variety of methods that may be used to calibrate groundwater flow models, including both manual methods (e.g., trial-and-error) and inverse methods (e.g., PEST; Doherty and Hunt, 2010, and UCODE; Poeter et al., 2014). Calibration targets (the points in the model domain assessed for agreement) may include hydraulic heads, hydraulic fluxes, or if transport of solutes is included, solute concentrations (ASTM D5981-96; BLM, 2008). Although hydraulic heads are the most common calibration target, a minimum of one hydraulic flux calibration target should be included in groundwater flow models submitted to the Division to provide a check on water balances (if a reasonable calibration target for fluxes exists in the model domain).

One of the difficulties in model calibration is determining what is a "good enough" fit. This problem is generally addressed by assessing the adequacy of the solution for the intended use of the predictions (Reilly and Harbaugh, 2004). For example, a residual of 10 feet in one calibration target of a regional groundwater flow model may not significantly influence decisions made based on the model, unless that calibration target lies near a feature of interest in which 10 feet is an unacceptable uncertainty.

The degree-of-fit of groundwater flow models may be assessed both quantitatively and qualitatively. Quantitative tests for degree-of-fit include scatter plots with associated coefficient of determination (r^2) values, and calculations of the mean error, mean absolute error, root-mean-squared error, and the normalized root-mean-squared error (Anderson et al., 2015; ASTM D5490-93). Each of these quantitative measures has different benefits. A commonly used, if somewhat arbitrary, criterion to suggest a "good" calibration is a normalized root-mean-squared error of less than 10% for regional-scale groundwater models. In some cases, a greater or lesser root-mean-squared error may be more applicable. In many situations, it is informative to subdivide the model domain and assess calibration within different areas of the model. In this case, a normalized root-mean-squared error of 10% in a particular subdomain may be unacceptable. This would be the case if a higher degree of accuracy is required in the region of interest, such as in the situation of wells near dewatered pits, where the simulated heads and inflows have substantial impact on possible management options. The most common qualitative degree-of-fit tests are a comparison of the predicted and observed potentiometric surface, and comparison of predicted and observed hydrographs of calibration points.

The Division has noted a tendency to under-report the results of calibration in groundwater flow model reports, which is a major flaw in many reports because calibration information is one factor that can help address predictive uncertainty and is a necessary piece of information in reviewing groundwater models. In particular, the spatial variation of calibration residuals is a critical piece of information and must be reported and discussed along with all other appropriate calibration statistics. See the section on model reporting for additional information and requirements.

In addition to model calibration, it is also useful to test the capability of the model in predicting observed stresses in the model. This process is commonly known as history matching or verification. As discussed in Oreskes et al. (1994), the term verification should be avoided because groundwater flow models are non-unique. Regardless of terminology, once an adequate calibration has been achieved a period of

observed stresses on the system should be simulated, and the time period included in the history match should differ from that used in the calibration (BLM, 2008).

All models to be used for predictive purposes, which represent the majority of models submitted to the Division, must be calibrated and subjected to history matching, with results presented in modeling reports. The modeler is referred to Anderson et al. (2015), ASTM D5981-96, ASTM D5490-93, and Reilly and Harbaugh (2004) for additional information on model calibration, and BLM (2008) and Bredehoeft (2003) for information on history matching.

7. Specialized Modeling Applications

Some groundwater modeling codes have additional predictive capabilities that may be useful when applied to mining projects. The two most common specialized applications submitted to the Division are particle tracking and solute transport, which are described further below. This is not an exhaustive list of specialized modeling applications, however, and many other applications could be applied in a useful manner to mine sites.

Particle Tracking

Particle tracking is a tool that uses the results of a groundwater model simulation to calculate travel times and flow paths in the groundwater system. Various groundwater modeling codes include particle tracking abilities. One of the most commonly used particle-tracking codes is the MODPATH (Pollock, 2012) post-processing tool designed to be used with MODFLOW.

Results of particle-tracking calculations may be useful in interpretation of general groundwater flow model results. Some of the most common uses for particle-tracking results are to estimate groundwater age, to identify both recharge areas and discharge areas of the groundwater system, and to identify contributing areas to individual hydrologic features such as wells or streams. Additionally, particle-tracking calculations may be computed either forward or reverse in time.

There are a variety of factors affecting the predictive ability of particle-tracking codes including spatial discretization, temporal discretization, the treatment of sinks, and dimensionality of the simulated system (i.e., two-dimensional or three-dimensional). One common error observed by the Division is the crossing of particle tracks in two-dimensional models. This indicates an error in either the particle-tracking calculations or groundwater flow model because discrete groundwater flow paths may converge but never cross. The modeler is referred to Pollock (2012) for a more thorough discussion of particle-tracking limitations and common errors.

Solute Transport

Within the groundwater system, the transport of solutes (dissolved chemical species) is controlled by a variety of different processes, including advection (physical movement due to hydraulic gradient), dispersion (spread of flow paths due to tortuosity of aquifer material), diffusion (physical movement due to chemical gradient), and retardation or attenuation (decrease in physical movement due to adsorption or other geochemical processes). In general, advection, dispersion, and diffusion tend to increase the movement of solutes, while retardation decreases the movement of solutes (Appelo and Postma, 2005).

Solute transport simulations often require significantly more data to constrain initial conditions and boundary conditions, including initial solute distribution, information on solute sources and sinks through time, the predicted groundwater flow field, and the effective porosity of the aquifer material (BLM, 2008). For a thorough review of solute-transport modeling, refer to Konikow (2011).

Similarly to particle-tracking applications, different groundwater modeling codes have different capabilities to simulate solute transport. Although many groundwater modeling codes have the ability to simulate the basic processes controlling solute transport, many do not consider more complex geochemical processes in their analyses. Therefore, in many cases a geochemical transport simulation using a geochemical code, such as PHREEQC (Parkhurst and Appelo, 2013) or PHAST (Parkhurst et al., 2010), may be required by the Division to fully evaluate the evolution of solute concentrations in the groundwater system. The modeler is referred to the Division's Guidance for Geochemical Modeling of Mining Activities for additional background information and requirements.

8. Sensitivity Analyses and Assessment of Uncertainty

Sensitivity analysis is the process of altering input parameters (e.g., boundary conditions, hydraulic properties, etc.) in order to assess the influence of each input parameter value on the simulated conditions calculated by the groundwater flow model. The relative effect each parameter change has on the simulations helps to inform both a fundamental understanding of the groundwater system (Reilly and Harbaugh, 2004), and how relative uncertainties could impact predictions. Sensitivity analyses are critical in groundwater flow models submitted to the Division because the numeric value of many input parameters for groundwater modeling are relatively uncertain. Sensitivity analyses help to evaluate the range of alternative predictions that result from differing input parameters. In conducting sensitivity analyses it is important that the ranges of values used in input parameters are reasonable, as using unreasonable parameter values is of little practical use. Sensitivity analyses commonly use +50% of the measured or estimated input parameter value as a starting point if the parameter has relatively little variability (e.g., porosity). Sensitivity analyses for parameters that vary over orders of magnitudes (e.g., K and T) should use much greater variability in input values. It is also important to distinguish between the concepts of calibration sensitivity analysis, which minimizes residuals only during calibration, and sensitivity analysis, which examines the effects in both model calibration and prediction (ASTM D5981-96). These distinctions may be important when assessing model performance and uncertainty (Kelson et al., 2002).

There are a number of parameters that should be considered in all groundwater models for inclusion in sensitivity analyses. These parameters include K, porosity, recharge, specified-head or specified-flow boundary conditions, evaporation from pit lakes, and highwall runoff into pit lakes. Each of these parameters is difficult to measure in the field, and therefore has a high degree of uncertainty. While a sensitivity analysis using each parameter enumerated above may not be necessary for each groundwater model, at a minimum sensitivity analyses of K (or T) be incorporated. In simulations of the fate and transport of aqueous constituents, porosity (specifically effective porosity) should be included in sensitivity analyses. Other parameters incorporated into sensitivity analysis will vary based on conditions at the mine site. The Division may also require additional sensitivity analyses during model review.

Sensitivity analysis results may be used both qualitatively and quantitatively. The qualitative use of sensitivity analyses generally includes an examination of the predicted groundwater flow field, hydrographs at calibration or observation points, or other graphical outputs. Quantitative examination of sensitivity analysis results could include a comparison of calibration measures in the base-case and sensitivity predictions, or calculation of the parameter sensitivity, which is the change in output head or flow divided by the change in the input parameter (Reilly and Harbaugh, 2004).

As a result of sensitivity analysis the modeler typically identifies parameters that are either sensitive (having a significant effect on model predictions) or insensitive (having negligible effect on model

predictions). Ongoing hydrogeologic characterization work should then focus on sensitive parameters so that future modeling efforts will rely on more refined parameter values.

The results of both sensitivity analyses and calibration may be used to estimate the uncertainty in model predictions of future conditions, if applicable for a specific model. Groundwater models intrinsically contain uncertainty, because they are built on a simplified conceptual model of the actual system and because our history of observations is nearly always less than the period of the prediction. It is important for model reports to address this uncertainty. One method of assessing uncertainty is to include a performance assessment of short-term model predictions from the previous model iteration, and compare how those previous predictions matched, or failed to match, observed conditions (Bredehoeft, 2003; 2005). Through the process of the performance assessment, the conceptual model may need to be altered and data needs can be evaluated. This iterative process should increase the overall usefulness of predictive groundwater models through time. Because the performance assessment can lead to new insights into the groundwater system, this step could also be performed at the beginning of the model update process. Additionally, results of the performance assessment should be used to give an overall sense of model uncertainty.

It should be noted that the concepts described above do not include a truly quantitative measure of uncertainty for predictive simulations, which would require stochastic methods. An example of a quantitative uncertainty analysis would be a prediction of the 95% upper confidence interval for predicted hydraulic heads. These types of uncertainty analysis are useful for groundwater models but are not typically required for submittals to the Division.

9. Predictive Simulations

In the majority of cases, groundwater models submitted to the Division are used for predicting the future hydraulic conditions (e.g., hydraulic heads, groundwater fluxes, etc.) in an area of interest, in this case the mine site and appropriate surroundings.

One of the most important aspects to consider when predicting groundwater conditions in reference to possible environmental impacts is conservatism. Environmental conservatism generally states that when there is uncertainty regarding the values of input parameters and associated predictions, appropriate values should be selected to emphasize the higher range of possible impacts to natural resources. By building conservatism into predictive models it is likely that the actual impacts to the natural system will be less than predicted. However, a balance must be achieved between realism and conservatism. If a model (either conceptual or numerical) is so conservative that the predictions are physically unreasonable, the model is of little use in decision making. Additionally, an input value that may be conservative for one aspect of the model may be non-conservative in another aspect. For example, a groundwater model predicting a large pit lake may be conservative from a sense of the ultimate effect of pit-lake evaporation on the groundwater flow system, but the same model would not be conservative, however, in terms of the water-quality of the pit lake. In this example the large pit lake would likely result in more dilute concentrations of aqueous constituents, and therefore may underestimate the ultimate effect the pit lake will have on the surrounding environment. This example does not contain the complicating effects of potential pit-lake flow through, residence time, or important geochemical processes, but nonetheless shows how conservativism could be approached.

A common consideration when predicting future groundwater conditions is the length of time for which predictions should be carried out. The Division has encountered numerous prediction intervals based on differing criteria including until predicted pit lakes have reached 90% of their ultimate predicted volume, until predicted pit lakes have reached 90% of their ultimate predicted depth, until annual groundwater

fluxes vary by less than 10% of their long-term predicted average, and others. The time interval of predictions varies on a project-by-project basis, and as such, the Division makes no strict rules for this aspect of groundwater modeling. The rationale for the period of predictions, however, should be logically determined and described in the model report.

As a part of ongoing monitoring activities, it is essential to compare the short-term predictions of the previous model with field conditions since that model's preparation. These comparisons could include hydraulic heads and fluxes, dewatering rates, and geochemical considerations. By assessing the performance of the predictive model versus observations during the intervening time period additional information will be learned about the groundwater flow system, which will help to refine the conceptual and numerical models for future updates (BLM, 2008; Bredehoeft, 2003). Therefore, it is essential that all models include both short-term and long-term predictions. The short-term period of assessment generally corresponds to the WPCP renewal timeframe of five years, as updated groundwater flow models are commonly included in continuing investigations requirements in the WPCP. However, alternative groundwater modeling frequency may be required by the Division based on site-specific concerns.

10. Model Reporting

The final step in groundwater flow modeling is the reporting of predictions to the relevant stakeholders – in this case the mining operator, the Division, and the public. It is essential for model reporting to be transparent, accurate, and include all necessary components. Numerous details and considerations with respect to model reporting are outlined in Anderson et al. (2015), ASTM D5718-95, Barnett et al. (2012), BLM (2008), and Reilly and Harbaugh (2004).

The requirements for model reporting to the Division are broadly similar to those for reporting to the BLM (BLM, 2008). Also, Barnett et al. (2012) includes a checklist of aspects of the groundwater flow model that should generally be included in the model report. The specific requirements and considerations for model reporting to the Division are described in Attachment A. This list is not meant to be overly prescriptive; each item included in Attachment A need not appear with the exact title in modeling reports, or in the same order. Additionally some reports may include sections not listed in Attachment A. However, outright omission of any items applicable to the specific project included in Attachment A will result in the groundwater model report being deemed incomplete. The template the Division will use to review groundwater models is also supplied in Attachment A. This template will serve as a review record for each groundwater model submitted to the Division.

Conclusion

In summary, groundwater flow models are commonly required to be submitted to the Division to assess the potential for groundwater degradation, as described in NAC 445A.424. The predictions of these models help to inform an understanding of the likely hydraulic conditions on mine sites, both in the present and in the future.

Predictions are often used in conjunction with other types of predictive models, including pit-lake models or models of contaminant fate and transport. For specifics related to the prediction of geochemical quantities the reader is referred to the Division's Guidance for Geochemical Modeling of Mining Activities.

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Attachment A: NDEP-BMRR Groundwater Model Review Checklist

This is a list of aspects of hydrogeologic significance that should be reviewed for each groundwater modeling report. For additional information on any specific aspect mentioned here the reader is referred to the following documents:

Anderson, M.P., Woessner, W.W., and Hunt, R.J., 2015, *Applied groundwater modeling: Simulation of flow and advective transport*, Academic Press, pp. 564.

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A., and Boronkay, A., 2012, *Australian groundwater modelling guidelines*, Waterlines report series no. 82: National Water Commission, Canberra, pp. 203.

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Part 1 – Report Information (Include the following)

Project Name:

Permit Number:

Model Type (choose one):   Analytical   Analytic Element   Numerical

Code:

Part 2 – Contents of Report

Text Sections

Report Section:	Response: (Y/N)	Notes:
1. Title, project name, permit number, preparer, and date		
2. Executive summary		
3. Site background		
4. Study objectives and application/need for groundwater modeling		
a. Application of modeling methods (i.e., analytical versus numerical)		
b. Numerical code(s) used, and reasoning for application (if applicable)		
i. If the code(s) were modified in any way for the application at hand, appropriate material corresponding to the modification must be submitted, see specifically Anderson et al. (2015), Chapter 11.		
c. Performance assessment of previous model iteration (if applicable)		

Report Section:	Response: (Y/N)	Notes:
5. Description of groundwater flow system of interest		
a. Geologic framework		
b. Hydrologic framework (groundwater and surface water)		
c. Climatologic characteristics		
d. Current and past hydraulic conditions, and geochemical conditions (if applicable)		
6. Description of the conceptual model and model domain		
7. Description of the numerical model (if applicable)		
a. How the conceptual model was translated to the numerical model, including spatial and temporal discretization		
8. Description of boundary conditions		
9. Description of water budget(s), and comparison to previously published estimates (if applicable)		
10. Description and evaluation of aquifer properties and fluxes		
a. Sources for aquifer properties and fluxes included in the model		
b. Reasonable ranges for aquifer properties and fluxes		
11. Description of any applied hydraulic stresses		
12. Summary of steady-state calibration		
a. Calibration measures		
b. Interpretation of spatial variability of calibration residuals and impact on predictive modeling (if applicable)		
13. Summary of transient calibration (if applicable), to include calibration measures, as well as other applicable simulations (e.g., particle tracking, etc.)		
a. Calibration measures		

Report Section:	Response: (Y/N)	Notes:
b. Interpretation of spatial and temporal variability of calibration residuals and impact on predictive modeling (if applicable)		
14. Summary of history matching (if applicable)		
15. Summary of predictions (if applicable)		
16. Summary of sensitivity analyses		
a. Quantitative comparisons of results of the base-case model with sensitivity analyses, and discussion of how likely the sensitivity analysis scenario results are and how these likely scenarios affect long-term management/outcomes		
17. Conclusions of the study		
18. Appendices		
a. Geographic location and associated information for all hydraulic condition measurement points (monitoring wells, stream gauges, etc.), reported in accessible numerical format (e.g., CSV, Excel, etc.) with appropriate metadata (datum, coordinate system, etc.), or in geographic information system (GIS) file formats (e.g., .shp, .gdb, etc.)		
b. Geochemical analysis results (if applicable), reported in accessible numerical format (e.g., CSV, Excel, etc.)		
c. Calibration hydrographs (both steady-state and transient [if applicable])		
d. Aquifer testing results (or reference to associated document)		
e. Model input files (in electronic format)		
f. GIS files (e.g., .shp, .gdb, etc.) for ultimate pit topography and geology (if applicable)		

Figures

Report Figure:	Response: (Y/N)	Notes:
1. Geologic map and cross section(s), with scale, north arrow, and legend, as applicable		
2. Locations of hydraulic condition measurement points (e.g., monitoring wells, stream gauging stations, etc.)		
3. Potentiometric surface map and cross section(s) for current conditions		
4. Spatial discretization of the model grid and location of boundary conditions (if applicable)		
5. Calibration results (both steady-state and transient [if applicable]), plotted to show observed heads (or fluxes) versus simulated heads (or fluxes)		
6. Calibration residuals (both steady-state and transient [if applicable]), plotted in map-view to show the spatial distribution of residuals		
7. Predicted fluxes into or out of pit lakes, including flows from different hydrogeologic units (if applicable)		
8. Pit-lake filling curves (stage elevation, depth, etc.) (if applicable)		
9. Predicted potentiometric surface map(s) and cross section(s) (if applicable)		
10. Extent(s) of drawdown at one or more discrete time steps and extent of maximum drawdown (if applicable)		

Tables

Report Table:	Response: (Y/N)	Notes:
1. Climatologic characteristics (e.g., annual or monthly precipitation and evaporation)		
2. Hydraulic properties of hydrogeologic units and associated data sources (aquifer testing, other reports, etc.)		
3. Calibration results (both steady-state and transient [if applicable]), to include all relevant calibration statistics		

Report Table:	Response: (Y/N)	Notes:
4. Groundwater budgets for the model domain (for any applicable period of the model simulation), with comparison to published/targeted quantities (if applicable)		
5. Pit-lake budget(s) including quantities of inflow and outflow to different hydrogeologic units (if applicable)		
6. Parameter values used in sensitivity analyses		

Part 3 – Model Review

General Considerations

Consideration:	Response: (Y/N)	Notes:
Are the objectives of the study and the level of confidence clearly stated?		
Does the numerical or analytical model selected for use simulate the important physical processes needed to adequately represent the system?		
Are the uncertainties associated with the model clearly stated?		
Are all required sections of the report present (including figures and tables)?		

Modeling Approaches

Consideration:	Response: (Y/N)	Notes:
Is the overall approach (calibrated model, hypothetical system model, sensitivity analysis, superposition, and particle tracking) used in addressing the objectives clearly stated and appropriate?		
If the analysis is not three dimensional, is the representation of the system using one or two dimensions appropriate to meet the objectives of the study and justified in the report?		
If the model is steady state, is adequate information provided to justify that the system is reasonably close to a steady-state condition?		

Conceptual Model

Consideration:	Response: (Y/N)	Notes:
Is the conceptual model of the system under investigation reasonable?		
Are all physical processes and features within the model domain incorporated into the conceptual model?		
Is the conceptual model supported by representative data?		
Are there alternate conceptual models that could be reasonably applied?		

Model Discretization and Hydrogeologic Framework

Consideration:	Response: (Y / N)	Notes:
Are all processes included in the conceptual model also included in the numerical model?		
Does the horizontal discretization represent the important features of the hydrogeologic framework to meet the objectives of the study?		
Are the physical boundaries represented appropriately in space by the discretized representation?		
Is the horizontal discretization appropriate to represent the degree of complexity in the aquifer properties and head distribution (flow system)?		
Does the vertical discretization adequately represent the vertical connectivity and properties of the hydrogeologic framework to meet the objectives of the study?		
If the groundwater system is unconfined in some areas, then is the treatment of changes in saturated thickness and the potential for cells to go dry explained and appropriate? If cells have gone dry, does the resultant solution seem appropriate?		
Is the temporal discretization fine enough to represent the degree of complexity in stresses and head distribution over time?		

Boundary Conditions

Consideration:	Response: (Y / N)	Notes:
Are the mathematical representations of the boundary conditions reasonable for the objectives of the study?		
Are all the external boundaries of the model associated with a definable physical feature?		
If no:		
a) Is justification provided for the use of artificial boundaries?		
b) Is the justification sufficient?		
c) Are the effects of the artificial boundaries tested in the calibration of the model and documented in the report?		
d) Does the documentation of their use and their testing make a convincing argument for their reasonableness?		
If yes:		
a) Is the mathematical representation of the physical feature appropriate?		
b) Are there conditions under which the representation of the boundary used in the model would become invalid?		
c) Are these conditions discussed?		
Do the boundary conditions of the model overly constrain the model results so that the calibration is insensitive, and the predictions are not realistic?		

Transient Solutions

Consideration:	Response: (Y / N)	Notes:
Does the transient model simulation start from a steady-state condition?		
If yes:		
a) Were the initial conditions generated from a steady-state simulation of the period of equilibrium?		

Consideration:	Response: (Y / N)	Notes:
b) If the initial conditions were not generated from a steady-state simulation of the period of equilibrium, is there a compelling reason why they were not generated, or are the initial conditions invalid?		
If no:		
a) Was it possible to select a period of equilibrium to start the simulation and make the determination of initial conditions more straightforward? If it is possible, then the model should have simulated the transient period from the period of equilibrium.		
b) If it was not possible to select a period of equilibrium to start the simulation, then what was the justification for selecting the starting time and the initial conditions for the simulation?		
c) How was it shown that the initial conditions used did not bias the result of the simulation?		

Adequacy of Calibration

Consideration:	Response: (Y / N)	Notes:
Does the simulated head and flow distribution mimic the important aspects of the flow system, such as magnitude and direction of the flow vectors?		
Does some quantitative measure of head and flow differences between the simulated and observed values seem reasonable for the objectives of the investigation?		
Does the distribution of areas where simulated heads are too high and areas where simulated heads are too low seem randomly distributed? If they are not randomly distributed, then is there a hydrogeologic justification to change the model and make the residuals more random aerially?		
Has a short-term performance assessment been completed (e.g., a history match), and if so are the results acceptable?		

Uncertainty and Sensitivity Analysis

Consideration:	Response: (Y / N)	Notes:
Has the sensitivity analysis included reasonable parameters and parameter values to encompass possible conditions on the site?		
Are the sources of uncertainty discussed?		
Has some quantitative or qualitative assessment of uncertainty been made?		
Have suggestions to reduce uncertainty in future models (e.g., data gathering, additional testing, etc.) been included?		

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