Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities

British Columbia
Ministry of Environment

Water Protection & Sustainability Branch

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April 2012

REPORT NO. 194001

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ACKNOWLEDGMENTS

Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities has been written by: Dr. Christoph Wels (Robertson GeoConsultants Inc.), Dan Mackie and Jacek Scibek (both of SRK Consulting (Canada) Inc.). Lawrence Charlebois (Robertson GeoConsultants Inc.) compiled the case studies and assisted with final preparation of this document. Jack Caldwell (Robertson GeoConsultants Inc.) provided internal review and served as technical editor of these guidelines. The Project facilitator/coordinator was Mike Wei (Ministry of Environment).

These guidelines were developed in close consultation with a steering team which included Mike Wei (Chair, Ministry of Environment), Vicki Carmichael, Scott Jackson, Klaus Rathfelder (all of Ministry of Environment), Gwyn Graham (Environment Canada), Trish Balcaen and Audrey Roburn (both of Environmental Assessment Office). The steering team provided guidance and review of these guidelines. The authors wish to thank the steering team members for their contributions to this document.

External review of these guidelines was provided by Andarge Baye, Pat Lapcevic, Michele Lepitre, Mike Simpson (all of the Ministry of Forests, Lands and Natural Resource Operations) and Alanya Smith (Environmental Assessment Office).

The authors would also like to acknowledge the individuals responsible for the modelling work presented in the Case Studies in Appendix C: Mr. Rod Smith, Schlumberger Water Services (Case Study 1), Dr. Jean Cho, independent consultant (Case Study 2), and Mr. David Tiplady, Piteau Associates (Case Study 3). Their review comments on the Case Studies and provision of supporting material is greatly appreciated.

Funding for this document was provided by the BC Ministry of Environment under contract GS12ESD-116 to Robertson GeoConsultants Inc.

1 INTRODUCTION

1.1 GENERAL

These guidelines were commissioned by the Ministry of Environment of British Columbia (BC MoE) under contract GS12ESD-116 and are referred to as “groundwater modelling guidelines” or simply “guidelines” throughout this document.

These guidelines were written by Dr. Christoph Wels (Robertson GeoConsultants Inc.), Dan Mackie and Jacek Scibek (both of SRK Consulting (Canada) Inc.). The authors have over 40 years of combined experience in groundwater modelling for the mining and groundwater resource industry.

1.2 NEED FOR GUIDELINES

The development of natural resources in British Columbia includes hard-rock mining, aggregate mining, and groundwater extraction projects. Development, operation, and closure of such projects involve an assessment of environmental impacts before a project can be approved by the regulatory agencies. Note that oil and gas developments may also use significant amounts of groundwater resources. Although this industry sector is not covered explicitly included in these guidelines, the general principles discussed in these guidelines may also apply to that sector.

The scale and nature of mining projects and large groundwater extraction projects may impact the receiving environment (including groundwater and/or surface water). The impact needs to be quantified prior to undertaking the project.

Recent advances in computing power and user-friendly modelling software have made the use of numerical groundwater models for impact assessments common. Table 1-1 lists mining and groundwater extraction projects that submitted full Environmental Assessment (EA) applications and were accepted for review by the B.C. Environmental Assessment Office (EAO) in the last decade. A review of the groundwater modeling studies completed for these projects indicates that most proponents used numerical groundwater models to support their (EA) application.

The use of numerical groundwater models enables decision makers to study and evaluate large and complex resource development projects. Sophisticated models and modelling platforms are, however, no guarantee of good modelling practice. The complexities of groundwater models used for impact assessment may even lead to misuse and/or misinterpretation.

To address the complexity and avoid potential misuse of groundwater models, there is a need to provide guidance to industry and government agencies on how to develop, use, and review groundwater models used to assess environmental impacts due to mining and large groundwater extraction projects.

These guidelines address the broader concepts of groundwater modelling related to the EA process in British Columbia. Yet, these guidelines reflect generally accepted best practices in groundwater modelling and as such should be applicable to a wider range of groundwater modelling applications.

Table 1-1: Recent uses of groundwater modelling in EA applications (continued on following page)

Project Name	Location	NR Project Type	GW Issues	GW Flow Modeling	Transport Modeling
Bevan Avenue Wells Project	Abbotsford	GW Extraction	Creek baseflow; Zone of Influence (ZOI)	3D Transient Regional Model (MODFLOW);	-
Chemainus Wells Water Supply Project	District of N. Cowichan	GW Extraction	Impacts to Chemainus River Aquifer;	3D SS Model (MODFLOW);	-
Cranbrook Deep Wells Project	Cranbrook	GW Extraction	Effects from contaminated sites; impact on local wetland and lake	3D SS Model (MODFLOW);	Particle tracking
Kamloops Groundwater Project	Kamloops	GW Extraction	Capture zone	3D Flow Model (MODFLOW); [*]	Pathline analysis
City of Prince George - Fishtrap Is. Collector Well	City of Prince George	GW Extraction	Capture zone; Aquifer drawdown	3D Flow Model (MODFLOW);	-
Basal Aquifer Dewatering	Highland Valley Copper, Logan Lake	GW Extraction	GW supply; Discharge to brook	3D Transient Valley-wide Model (MODFLOW);	-
North Lakeside Well	Williams Lake	GW Extraction	Drawdown; capture zone	[*]	[*]
Squamish Groundwater (1999)	Squamish	GW Extraction	Baseflow impacts; Capture zone	FD Flow Model	-
Dist. of Chilliwack Groundwater Well Project (1998)	District of Chilliwack	GW Extraction	Aquifer protection; contamination risk	Analytical (Theis) drawdown; Capture zone based on Regional Flow Model (not avail.)	-
Morrison Copper/Gold Project	65 km NE of Smithers	Mining	Pit Inflow; TSF Seepage to small creeks & Morrison Lake; WRD seepage to Morrison Lake; seepage from backfilled pit to Morrison Lake	3D SS Model (TSF); 2D SS Model (Open Pit);	3D Transport Model (TSF only)
Davidson Project	9 km NW of Smithers	Mining	Adit seepage; closure	3D SS and Transient Regional Model (MODFLOW);	MODPATH/MT3D (regional, 100 yr)
Roman Coal Mine	25 km S of Tumbler Ridge	Mining	Pit inflow; TSF seepage; WR seepage;	2D SS SEEP/W (project site); Analytical (pit, TSF, WR) [Dupuit-Forchheimer]	Analytical
Prosperity Gold-Copper Project	125 km SW of Williams Lake	Mining	Pit Inflow; Stream baseflow; TSF seepage to nearby streams and lakes	3D Transient Model (MODFLOW);	3D Transport model (MT3DMS)

Key:
GW Extraction
Mining
Aggregates

ABA - Acid-Base Accounting
FD - Finite Diference
FE - Finite Element
GW - Groundwater
K - Hydraulic Conductivity
TSF - Tailings Storage Facility

SS - Steady State
WB - Water Balance
WR - Waste Rock
WL - Water Level (static unless otherwise noted)
[*] - Report not reviewed at the time of preparing these guidelines

Project Name	Location	NR Project Type	GW Issues	GW Flow Modeling	Transport Modeling
Mt. Milligan Copper/Gold Project	N of Fort St. James	Mining	Pit Inflow; Reduced GW discharge to Alpine Creek and Meadow Creek; TSF seepage to creeks and GW; impacted pit wall inputs to post-closure pit lake	Regional 3D Model (MODFLOW-SURFACT); 2D Vadose/W seepage model sections (TSF); Analytical methods for pit inflow	Particle tracking
Hermann Mine Project	16 km S of Tumbler Ridge	Mining	Reduced baseflow to M20 and M14 creeks; sewage effluent	WB calibrated to surface flows	-
Tulsequah Chief Project	Taku River, S of Atlin	Mining	[*]	[*]	[*]
Ruby Creek Molybdenum	24 km NE of Atlin	Mining	Pit Inflow; TSF seepage; Discharge to Ruby Creek and Surprise Lake	Analytical (Darcy); Stream Flow; Catchment Area and Infiltration; 2D SEEP/W (TSF);	Loading and dilution factors (surface waters)
Galore Creek Copper-Gold-Silver Project	150 km NW of Stewart	Mining	Infrastructure seepage; Pit inflow; TSF seepage;	3D watershed model (MODFLOW); 2D Seepage Analysis (TSF dam only)	[GoldSim; ABA]
Brule Mine Project	57 km S of Chetwynd	Mining	Pit inflow; TSF and WR seepage; discharge to ditches and Blind Creek	no	no
Red Chris Porphyry Copper-Gold Mine Project	18 km SE of Iskut	Mining	TSF seepage; Pit inflow; discharge to creeks; closure	3D SS MODFLOW w/ transient calib. (regional)	MODPATH
Wolverine Coal Mine	NW of Tumbler Ridge	Mining	Pit inflow; discharge to wetlands	2D SS SEEP/W (TSF only)	Loading and dilution factors (surface waters)
Swamp Point Aggregate Mine Project	50 km S of Stewart	Aggregates	Pit inflow; baseflow to creeks	no	no
Orca Sand and Gravel Project	4 km W of Port McNeil	Aggregates	Drawdown	3D SS MODFLOW (regional)	no
Eagle Rock Quarry Project	Alberni Inlet	Aggregates	-	no	no

Key:
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1.3 OBJECTIVES OF THE GUIDELINES

To the best of our knowledge no groundwater modelling guidelines are presently available for any Canadian jurisdiction and none of the international guidelines reviewed (see Appendix A) has a specific focus on resource industries such as mining and/or groundwater extraction.

The objective of this document is accordingly to provide guidelines for groundwater modelling undertaken to identify and assess the impacts of natural resource projects in British Columbia, with specific emphasis on:

- Hardrock mining (metal, coal)
- Aggregate Mining (gravel)
- Large groundwater extraction projects (>75 L/s)

These guidelines provide general guidance based on accepted “best practices” for:

- Development and use of groundwater models by resource industry groundwater professionals.
- Review of groundwater models by regulators.

1.4 TARGET AUDIENCE

This document was written for use by the industry[1] ("proponent") and regulatory staff or agency ("regulator") involved in the assessment of environmental impacts for natural resource projects in British Columbia using groundwater modelling. These guidelines assume that the reader has an understanding of hydrogeology and a basic understanding of groundwater modelling. Practical experience in groundwater modelling is not, however, required to use these guidelines.

These guidelines discuss basic concepts of groundwater modelling. The reader is strongly encouraged to study standard textbooks on hydrogeology and groundwater modelling if he/she has no formal training in these subject areas (see Appendix B for a list of recommended readings).

A supplementary online course (based on these guidelines) serves as a self-directed training tool for regulators involved in developing or reviewing groundwater modelling projects. This on-line training course can be accessed free of charge by the regulators and the wider public at the following URL: http://www.rgc.ca/moe/guidelines/.

1.5 SCOPE OF THE GUIDELINES

The guidelines include the following sections:

- ***Section 2 – Proponent-Regulator Interaction in the B.C. System,*** provides background information to groundwater modelling in the context of the British Columbian regulatory process. Specifically, this section describes the regulatory process as it affects preparation by the proponent (project developer) of groundwater models to support project review by the regulators who are charged with assessing the potential adverse effects of a proposed Project and making recommendations to the responsible Ministers for an Environmental Assessment Certificate, allowing a proposed Project to proceed to the permitting stage.

- ***Section 3 – Groundwater Modelling for Impact Assessment of Natural Resource Projects,*** describes the application of groundwater models for assessing the impact of resource development projects on the groundwater. Specifically, this section addresses what issues may be evaluated with groundwater models to establish potential impacts and identify mitigative measures for hard rock mining, aggregate mining, and groundwater extraction projects.

- ***Section 4 – Conceptual Model Development,*** describes the process of developing a conceptual model of the groundwater system at a specific site. The section establishes how information about the site geology, hydrology, potential contaminants, and project-specific features may be assembled into a conceptual model that forms the basis of the mathematical groundwater model.

- ***Section 5 – Mathematical Model Selection,*** describes the types of mathematical models that may be used to quantify groundwater flow and solute transport at a site both before and after

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[1] Industry means a person, company or entity who is in the business to develop a natural resource (e.g. mining or large extraction well project) and includes environmental and groundwater consultants in the business of doing the groundwater modelling and impact assessment work for the industry

initiation of the project. The section provides guidance on the selection of specific mathematical models.

- ***Section 6 – Numerical Model Setup,*** describes how to set up a mathematical groundwater model. The section deals with the technical approach to the definition of the model domain, numerical grid, boundary conditions, layers (that represent different geological strata), and how to mathematically represent sinks and sources, including those project facilities that may be the origin of contaminants to the groundwater.

- ***Section 7 – Model Calibration & Verification,*** deals with the calibration and verification of groundwater models. Calibration is a process of refining model parameters based on comparison of field data to model-predicted values. Verification is the use of alternative analytical techniques to establish the extent to which the select model is robust in its prediction of the groundwater flow system.

- ***Section 8 – Model Prediction & Uncertainty,*** describes how a groundwater model is used to predict in what way groundwater responds to the construction and operation of project facilities, including, for example, excavation of an open pit, placement of a tailings impoundment, or extraction of groundwater for project use. This section also discusses how to assess the uncertainty in model predictions.

- ***Section 9 – Transport Modelling,*** provides an overview of the methods used to model and evaluate the migration of contaminants of concern (CoCs) in groundwater that may impact the environment.

- ***Section 10 – Model Documentation,*** provides guidance for documenting groundwater modelling in order to facilitate review and approval by regulators.

- ***Section 11 – Model Review,*** provides guidance on for reviewing groundwater studies submitted by a proponent for review and project approval.

In order to illustrate the applicability of these guidelines, three representative case studies were also included in these guidelines (see Appendix C). These case studies include:

- A proposed open pit mine (hardrock)
- A proposed underground mine (hardrock);
- A proposed large (>75 L/s) groundwater extraction project (surficial)

1.6 LIMITATIONS

Every resource project has a unique combination of site conditions, project activities, and modelling requirements. Professional judgment by the modeller, based on experience, and specific conditions and requirements of a project or a site, is required to select the best approach to modelling a particular site and project. These guidelines therefore provide generally applicable guidance and a framework for groundwater modelling. The guidelines do not set prescriptive standards.

Professional judgment introduces subjectivity into the modelling process and may result in questions and debates within the regulatory process. These guidelines therefore recommend that the industry proponent consults the regulatory agencies on key aspects of the modelling project so any questions and debates can be addressed in a timely manner.

2 PROPONENT-REGULATOR INTERACTION IN THE B.C. REGULATORY SYSTEM

2.1 INTRODUCTION

2.1.1 Section Scope

This section provides a brief overview of the British Columbian regulatory process as it affects:

- Preparation by the proponent (project developer) of groundwater models prepared to support regulatory review of natural resource projects.
- Review of groundwater models by regulators who are charged with acceptance or rejection of the proponent's applications to proceed with the project.

2.1.2 General

In British Columbia (as in most jurisdictions in Canada), if a project meets or exceeds the thresholds in the reviewable projects regulations, an Environmental Assessment must be completed and an Environmental Assessment (EA) certificate issued before a resource project may proceed to permitting, construction, operation, and ultimately closure and restoration. In certain instances, such as projects that may have a deleterious effect on fish habitat, projects may require a Canadian Environmental Assessment. This subsection describes the activities leading up to issue of an EA certificate by the regulator (see Figure 2-1 for an example applied to a mine).

Further information on the British Columbia EA process can be found at:

http://www.eao.gov.bc.ca/

2.1.3 Phases of Regulator Interaction

The phases of project development and implementation at which the proponent may be submitting groundwater models to the regulators for review and approval are:

- Pre-Application – Model objectives & requirements; model plans.
- Environmental Assessment – Model reports with results.
- Permitting – Updated EA Models, if possible or required, or new models, reports and results.
- Operation – Updated EA or permitting models, if possible or required.
- Closure – Updated EA or permitting models, if possible or required.

2.1.4 Why A Groundwater Model?

Groundwater models may be compiled as part of the planning and implementation of a resource project and used to:

- Describe the groundwater flow system and the main processes that influence system behavior.
- Assess impacts (type, degree, extent) related to various project components (e.g., dewatering of a proposed open pit; potential reduction in baseflow from well pumping).
- Assess potential effects and mitigation options related to groundwater pathways.
- Guide impact management (i.e., mitigation and contingency measures).
- Communicate information to regulators and proponents.

Accordingly, this section presents an overview of how groundwater modelling can be used to support regulatory review of natural resource projects involving groundwater-specific issues.

2.1.5 Scheduling of Modelling Study

Groundwater modelling study schedules should be developed at an early stage in the overall environmental assessment process. As described later in this section, early identification of the need for and scope of, groundwater modelling is beneficial for the project schedule. If groundwater modelling is required, a modelling study schedule should reflect the estimated time for each of the model phases and the potential for iterations between data collection and model updates.

The following are representative modeling timeframes for different levels of model complexity (MDBC, 2001):

- Basic: < 1 month (available data are sufficient to achieve modelling objectives)
- Moderate: 1 to 6 months (some data collection and iteration may be required)
- Complex: > 6 months to several years (if used as a management tool during project development and ongoing data collection and iteration to improve model confidence are likely).

Model complexity and the modelling process are discussed in more detail in Section 3 of these guidelines.

The potential for delays can often be correlated with the need to collect additional data. Data collection that occurs during model development often requires updates to both the conceptual and mathematical models. If significant effort has been expended on mathematical modelling, additional data may require re-calibration, re-verification, and additional effort. As such, there is significant financial and schedule benefit to be gained by identifying data gaps early in the modelling process.

Despite best efforts, uncertainty as to the exact development plan is common at the early stages of mining and resource development projects. For example, during early stages of mine planning, planners and engineers are often assessing the financial benefits and trade-off of alternative mine development strategies, some of which can directly and significantly impact the objectives and modeling approach of the groundwater model.

The same may be said about management plans developed to quantify potential environmental effects. At an early stage in natural resource planning, the need for a specific management plan may not be identified or may be defined only at the level required to properly integrate with the groundwater model.

The groundwater model may have to be modified to address the management plan. In terms of groundwater extraction, management plans developed to address effects, such as increased depletion of surface waters, may be designed to minimize such impacts.

The personnel conducting the groundwater study need to retain good communication with project planners and other project team members to ensure that all components are synchronized. This requires significant effort and can often be the cause for project delays.

2.2 PRE-APPLICATION

2.2.1 General

The first step in proponent-regulator interaction is the pre-application phase, which includes data compilation and collection, and the preparation and submission of the Project Description for reviewable projects (Figure 2-1). The various phases of baseline groundwater modelling may be undertaken in conjunction with an environmental assessment (Figure 2-2). The pre-application phase of groundwater modelling includes work done prior to submission of the application for an EA certificate (Box 1 on Figure 2-2). Discussions with regulators are recommended at this stage about potential issues, baseline data collection requirements, and methods to complete effects assessments. Note that box numbers included on Figure 2-2 are for reference only and do not correspond to specific steps in the modeling process.

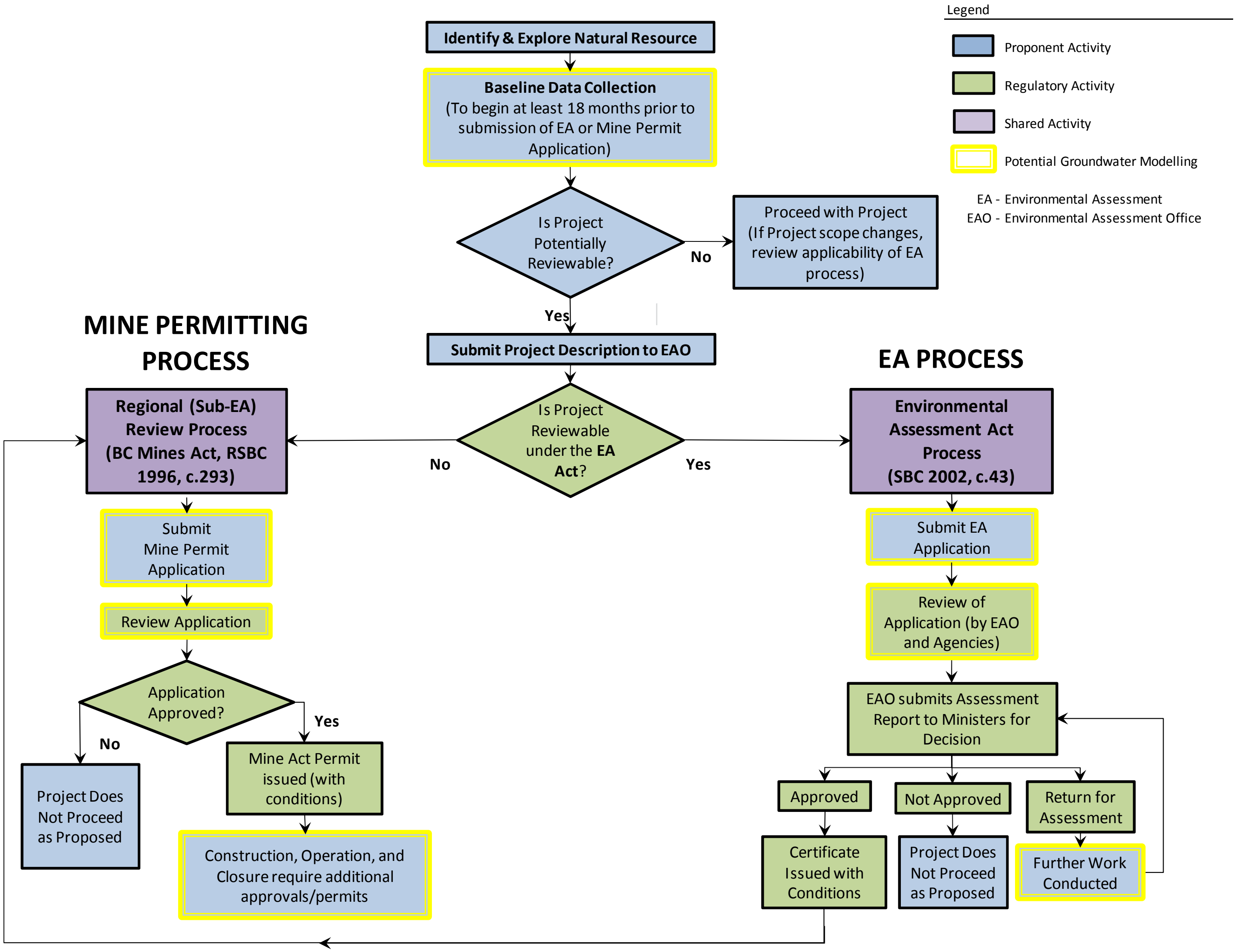


Figure 2-1: The mine approval process and groundwater modelling

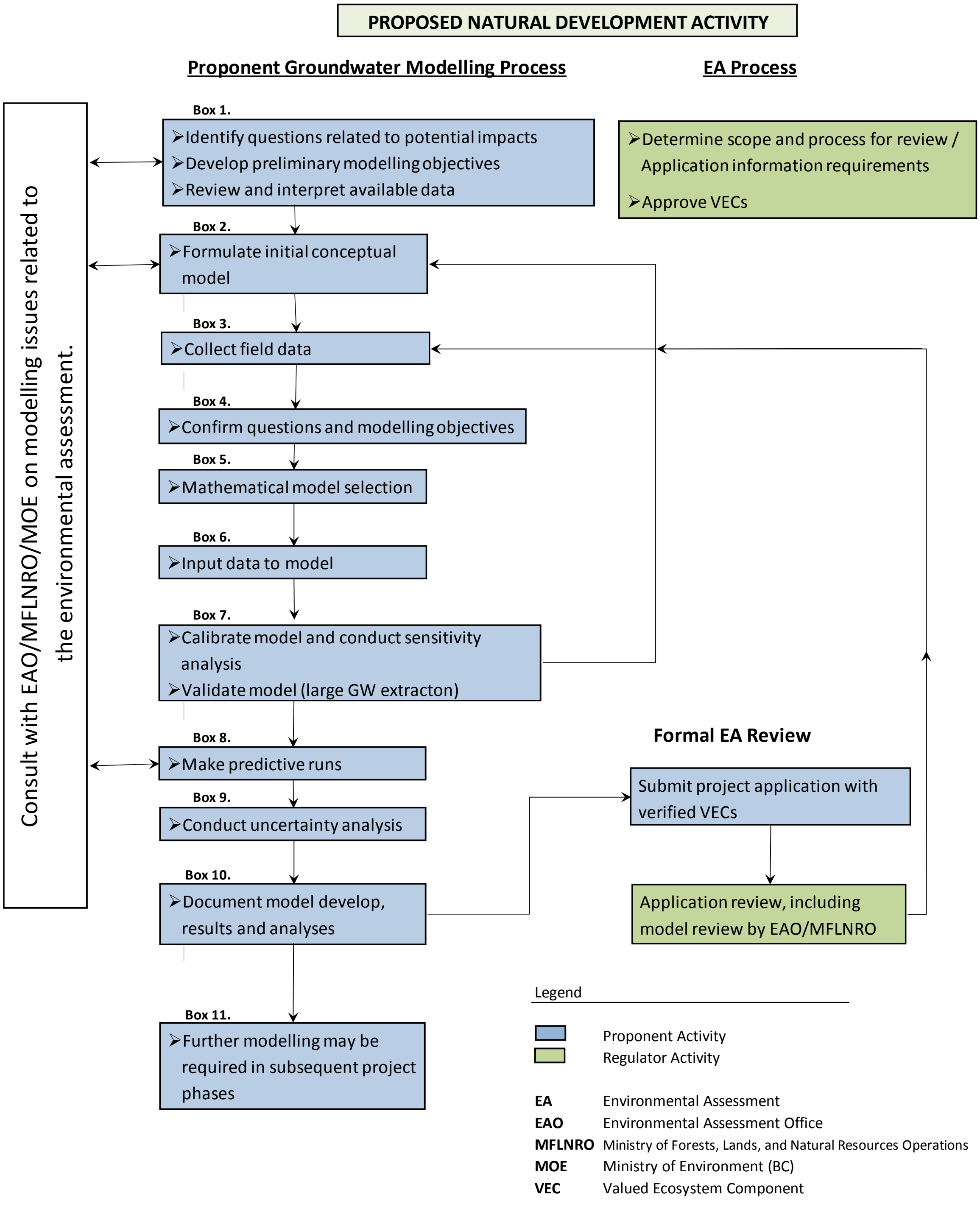


Figure 2-2: Groundwater modelling and the EA process

2.2.2 Application Information Requirements

If the EAO determines that a project is reviewable (based on predefined thresholds set out in the *Environmental Assessment Act, Reviewable Projects Regulation* under the *Environmental Assessment Act)* and a Section 10 order is issued, a working group of First Nations and government agencies is established and an application information requirements (AIR) is prepared by the Proponent, in consultation with the regulatory agencies. This should occur in parallel or after the Box 1 steps on Figure 2-2 are in progress. Once reviewed and accepted by EAO, the AIR establishes: the project study scope; the valued components to be studied; and the information to be included in the project application. If an EA is not reviewable, groundwater assessment requirements may be subject to other permits, but may not specifically require modeling.

During this phase, the following work related to groundwater modelling may be undertaken by the Proponent:

- Identify potential groundwater pathways for existing and proposed development conditions
- List potential contaminants of concern from proposed development.
- Identify potential impacts on groundwater resources and associated impacts to existing and future groundwater uses, including socio-economic and environmental uses.
- Initiate development of a conceptual groundwater model for existing and proposed conditions.
- Consult with regulators and the EA working group on how modelling can be used to support natural resources development and regulatory review.
- Define potential groundwater modelling objectives.
- Assess and prioritize groundwater modelling data needs.
- Develop a data collection schedule and begin (or continue) data collection. Baseline data collection for certain project valued ecosystem components (VECs) may have already been initiated, such as surface water flows and quality, ecological surveys, etc.

None of the work done during this pre-application phase (up to Box 4 in Figure 2-2) is likely to be final or definitive. The groundwater modelling process during the pre-application phase is very much an iterative process between definition of model objectives, data collection, conceptual model development, and possibly even preliminary mathematical modelling. On-going discussion with regulators, including the project EA working group is recommended throughout the pre-application phase.

2.2.3 Application Preparation and Submission

During this application preparation phase, the proponent commences (or continues) studies and information gathering as outlined in the AIR. From the perspective of groundwater modelling, this could be considered the formal starting point for the modelling process, although some components, such as baseline data collection, will already be underway to establish time trends or ranges for various parameters. If preliminary conservative calculations or analyses are being conducted, emphasis may still be placed on uncertainty analyses, but additional data are becoming available to allow a shift towards mathematical model calibration and sensitivity analyses, as required.

At this stage, regular consultation with regulatory agencies on the progress of groundwater modelling processes, initial findings and potential issues should be ongoing (see Figure 2-2). If formally required as part of the AIR, expectations should be clearly outlined but, even if not specifically outlined, the application preparation phase is the best opportunity for developing consensus on the assessment approach, which will help to avoid future delays related to insufficient information, methods, or outcomes. If not specifically required, it is during this phase that the proponent (and its contractors) has the opportunity to be transparent with and obtain input or guidance from regulators.

Assuming that the studies and information are acceptable, the application is submitted for review. If the application is determined by the EAO to be adequate, it will be accepted for review.

2.3 ENVIRONMENTAL ASSESSMENT

2.3.1 Groundwater Modelling Requirements

A groundwater model for an Environmental Assessment must establish at least the following:

- The baseline conditions are sufficiently well defined to enable the impact of the proposed activity to be reasonably assessed.
- The model is able to be used to reasonably model and quantify the impact of proposed activities on the groundwater and hence potential receptors.

In addition, the following are considerations for a groundwater modelling study undertaken in support of an Environmental Assessment (see Figure 2-2):

- Baseline or impact-specific data collection programs need to be of sufficient scope to allow model objectives to be realized.
- Model objectives may be broad in terms of result accuracy (e.g. order of magnitude), but must be sufficient to provide confidence that the predictions are assessed to a sufficient level.
- VEC’s, potential impacts and mitigation concepts (if not preliminary designs) need to be understood or available.
- Conservative assumptions should be used, and mitigations should be robust but not necessarily detailed to a high degree of specificity.

An EA model that concludes with significant adverse effects, or a high risk of significant adverse effects on groundwater, may result in an EA certificate not being issued unless the significant adverse effects can be mitigated to a level acceptable to the regulatory agencies.

2.3.2 Application Review

Once the application is accepted, the Environmental Assessment Office (EAO) has 180 days to review the application. This phase includes public review periods. The EAO starts preparing the draft assessment report. If the application has deficiencies, the time for review may be stopped (suspended) so the proponent can address the deficiencies.

This is when an in-depth review of the modelling studies supporting the EA is usually performed by the regulatory agencies (see Section 11).

2.3.3 Assessment Report

At the conclusion of the 180 day Application Review, the EAO submits its Assessment Report to Ministers. The Assessment Report includes conditions of the EA certificate to address environmental issues (e.g. to establish a monitoring program or commitment to implement a well-protection plan).

Conditions imposed on the proponent in regards to groundwater management or mitigation plans are a possible outcome of conservative assumptions used during the groundwater modelling process to address uncertainties or limited data. While conditions cannot necessarily be avoided entirely by improved data collection and model formulation, consultation earlier on in the process may reduce the requirement for conditions.

2.3.4 Minister's Decision & Permits

Once the Application Review is completed, the responsible Ministers have 45 days in which to decide whether to issue an EA certificate (EAC), or require additional information. At this stage, if the EAC is issued, the proponent may proceed with permit applications.

2.4 PERMITTING OF MINES

2.4.1 General

For the purposes of these guidelines, it is assumed that the Permitting Process follows after the issuance of an EAC. The EA may include agreed-on mitigation concepts or preliminary designs (if the potential exists for significant effects). During permitting, models may be improved with respect to calibration/verification based on additional data collection and analyses. If a project has not been required to undergo an EA, groundwater requirements may differ, depending on permitting requirements and regulatory agency. If an EA is not required, groundwater modeling may not be required.

2.4.2 Permitting Terms of Reference

In the Permitting Process, similar to the EA process, a terms of reference (AIR in EA) is required. As with the EA process, definition and review of the terms of reference (or AIR) provides an opportunity for consultation with regulatory agencies and the potential to avoid lengthening of the permitting process by addressing issues at an early stage.

2.4.3 Permits Other than EA

For mining or aggregate extraction processes, additional permits (e.g., under the *Mines Act* or *Environmental Management Act*) are required for which groundwater modelling may be necessary or justified. These include, Mine Permits, discharge permits or environmental effects monitoring programs.

Mine permit applications include sections on environmental effects. Often, when mining projects are progressing to the mine permitting stage, additional information may be available, either monitoring or mine planning, and the opportunity for additional groundwater modelling, such as model refinement, model verification, and/or post-audit exists.

Other permits that may require groundwater modelling include discharge or effluent permits. As these permits are typically applied for after issuance of an EA certificate, or perhaps a mine permit, groundwater models may already be sufficient for incorporation, if required. If groundwater modelling at a different level or for a specific area is required, and not appropriately addressed at an earlier stage, further effort and consultation may be required. Once operational data are available (e.g., drawdown in response to pit excavation), improved verification or re-calibration of the groundwater model using larger-scale stresses may be achievable.

Proponents may combine permit applications in a single package. In this case, the approach and information requirements may be such that a single groundwater model may be used for multiple applications.

2.4.4 Groundwater Modelling During Permitting

Mine permit work typically includes a focus on engineering designs, but opportunities for data collection in regards to impact assessments increase during work carried out in the course of this phase. Uncertainties identified during modelling at earlier stages may be targeted by specific site investigations. Mitigation concepts should be progressing in terms of engineering design, which are the focus of data collection programs aimed at providing a higher level of confidence of system effectiveness. Site investigations may identify issues requiring design modifications.

For this category of models, it is reasonable to expect a higher level of complexity (if warranted by a potential impact) and a reduced range of model parameters for uncertainty analysis. Model objectives may not change, but become narrower, or more constrained.

As more detail is often available, models (both conceptual and mathematical) may have to be reconstructed if the mine plan (or, for example, a seepage mitigation design) has changed and/or new field data indicate that the old conceptual model is no longer valid.

2.4.5 Mining Operations

Mining operations begin once the permits are in place. Groundwater monitoring is undertaken during mining.

BC mines are required to periodically renew closure plans and discharge permits. This involves submittal of data and reports to the regulator. It may be necessary and appropriate to update groundwater models and include results as part of the submittal. Since mining imposes significant stresses on the groundwater system, and the monitoring data quantify the impact, this detailed knowledge allows for better calibration of existing models or for development of more complex models and reduced uncertainty. As discussed above, additional information could also necessitate changes to the site conceptual model.

Groundwater modelling during operations can be part of environmental effects monitoring (EEM) or used to assess groundwater management plans. Modelling of potential impacts or updates of models, may be required for renewals of permits and/or applications for mine expansion. If impacts are observed during active mining, mitigation measures may be designed using groundwater models, or regulators may request a model or model update to address reasons for non-compliance with permit conditions, such as seepage at greater than predicted concentrations.

2.4.6 Mine Closure

Closure (and restoration) plans are required at both the EA and Mine Permit stages, and updates are required as part of permit amendment applications and renewal of other permits. For this category of models, a significant level of modelling may be required for impact assessment. In addition, source terms will be better defined and some (limited) calibration of transport modelling may be possible. However, large time frames for closure predictions (>100 years) can still result in large uncertainty requiring conservative assumptions and uncertainty analysis.

2.5 PERMITTING GROUNDWATER EXTRACTION

For groundwater extraction projects with withdrawal rates of 75 l/s or more, groundwater modelling and effects assessments are typically completed **during** the EA process. Although construction and operating permits may be required to operate the well as part of a water supply system, currently in BC, extraction of groundwater is not subject to a specific permitting process. While monitoring and well protection programs may have been initiated and on-going, unless specified in the EA certificate or as part of a management plan, additional modelling might be carried out, but is not mandatory.

2.6 GENERAL GUIDELINES FOR PROPONENT-REGULATOR INTERACTION

Most groundwater flow and contaminant transport models which are developed to assess environmental impacts of natural resource projects have to be submitted to the regulatory agencies for review and approval.

Every project has unique project objectives and site conditions and a series of subjective decisions have to be made throughout the modelling process. This subjectivity in modelling can result in disagreement during the review process. For example, what may be an acceptable methodology or assumption for the project modeller, may not be acceptable to the reviewer.

Considering the high degree of professional judgment and the significant lead times (and cost) required for groundwater modelling, early and ongoing consultation between the proponent and the regulator throughout the modelling process is recommended (see Figure 2-2).

Ideally, consultation with the regulatory agency should start at the outset of the modelling project and should establish (adapted from NGCLC, 2001):

- Study objectives (including legislative and policy context) and preliminary modelling objectives.
- Agreement on the initial or interim conceptual model.
- Agreement on the priorities for site investigation.
- Reporting requirements.

Depending on project complexity and sensitivity, subsequent consultation may include establishing agreement on:

- The conceptual model
- Modelling objectives
- Choice of mathematical model and modelling approach
- Scope of model calibration
- Scope of model predictions (e.g. which scenarios)
- Scope of sensitivity/uncertainty analysis (e.g. range of input parameter values)
- Reporting requirements.

Agreements are based on the information available at the time of review and may be subject to change. As additional data become available, additional potential effects are identified or addressed, or if modelling objectives are adjusted, further discussion of the above points may be required.

For complex and/or sensitive resource projects, the consultation should include technical experts from both sides (e.g. technical staff or external peer reviewer representing the regulatory agency and consultants representing the proponent) to assist in the technical aspects of modelling.

Ongoing consultation ensures that agreement is obtained at key stages of the modelling project rather than waiting until the work is completed before areas of disagreement are identified. This way concerns by the regulatory agency are addressed in a timely manner and unnecessary delays in permitting (say due to additional site investigations and/or modelling) are minimized.

SUMMARY POINTS FOR PROPONENT-REGULATOR INTERACTION IN THE B.C. REGULATORY SYSTEM

1. Groundwater models may be used during the environmental assessment process to understand groundwater flow systems and processes, assess impacts and mitigation options, guide management plans, and communicate information.
2. Groundwater modelling study schedules should be developed early in the process of assessing potential environmental effects.
3. Delays in permitting can often be correlated with the need to collect additional information, sometimes in relation to changes in project plans or management strategies.
4. Proponents should work with regulators during the environmental assessment pre-application stage to define the need and scope for groundwater modelling. This interaction should continue throughout the process.
5. For mining projects (hardrock or aggregate), additional permits will likely be required following receipt of an EA certificate. Groundwater modelling conducted during the EA application process may be suitable for these additional permits but, typically, more information or more detail may be required. Updates to groundwater models may be required during the permitting stage.
6. For mining projects, additional information collected during operations will become available for updating groundwater models. Uncertainty is typically reduced by utilizing this data.
7. For groundwater extraction projects having withdrawal rates of 75 L/s or greater, groundwater modelling is typically a requirement.

3 GROUNDWATER MODELLING FOR IMPACT ASSESSMENT OF NATURAL RESOURCE PROJECTS

3.1 INTRODUCTION

This section describes the basic concepts of groundwater modelling as applicable to mining, aggregate, and groundwater extraction projects. Although the concepts are generally applicable, the discussions focus on modelling related to the EA (and sub-EA) process.

3.2 DEFINITION OF GROUNDWATER MODEL

The term "Groundwater Model" can be found within the literature to mean different things to different people. Groundwater model is often used interchangeably for conceptual groundwater model or mathematical representation of a groundwater flow system (either analytical or numerical). In the broad sense, groundwater models can be considered as a sum of multiple components, both physically and mathematically based, each of which contributes to the general understanding of the processes that are operative in a groundwater system or the response to a specific question.

In these guidelines, the following definitions are used:

- "Groundwater Model": A generic term describing the sum of the components used to describe a groundwater system, including a conceptual and mathematical model.

- "Conceptual Model": The general description or representation of groundwater flow and transport at a site based on site-specific data or factors that influence hydrogeological processes. The ASTM definition for a conceptual model is "an interpretation or working description of the characteristics and dynamics of the physical system" (ASTM D5447-04, 2010).

- "Mathematical Model": A mathematical description of the groundwater flow system. The ASTM definition of a mathematical model is the "mathematical equations expressing the physical system and including simplifying assumptions. The representation of a physical system by mathematical expressions from which the behavior of the system can be deduced with known accuracy." (ASTM D5447-04, 2010).

Mathematical models can be of two types:

- "Analytical Model": A closed form solution (e.g. Darcy Law, Theis solution, advection-dispersion equation) of representative flow and transport equations. Analytical models are typically used to represent simple systems or to illustrate broad, generalized effects of different parameter assumptions.

- "Numerical Model": A computer model, using finite difference, finite element or other method, with an approximate solution of the governing flow and/or transport equations. The ASTM defines a numerical model as the "application of a mathematical model to represent a site-specific groundwater flow system" (ASTM D5447-04, 2010). Numerical models are typically used to represent more complex systems.

3.3 USE OF GROUNDWATER MODELS

Groundwater models are used to answer specific questions or to achieve a specific objective. Modelling objectives and methods vary depending on the nature of the question being asked and the characteristics of the site or system. The necessary level of detail or accuracy of results can vary, depending on the objective.

Within the natural resource industry, groundwater models are used for many purposes. In terms of environmental effects, models are used for environmental assessments or other permitting requirements. Typical uses of groundwater models include:

- Conceptualize and quantify current conditions (synthesize existing information)
- Understand system dynamics to identify and quantify controlling and significant processes (e.g., surface water – groundwater interactions, recharge areas, seepage rates, transport dynamics, etc.)
- Predict a future change or impact in response to a planned or potential stress, such as water table drawdown related to a planned extraction well or construction of a given mine plan component (e.g. inflow to an open pits, seepage from a tailings facilities, etc.)
- Evaluate sensitivity of the system to model uncertainty and/or magnitude of stresses
- Identify capture zones or source protection areas (for groundwater resource projects)
- Assess mitigation options (e.g. seepage interception, pump & treat etc.)
- Guide future data collection
- Improve the design of monitoring networks (e.g. determine aquifer units and/or specific areas requiring additional monitoring)
- Act as a management tool (e.g., assess different proposed management scenarios in managing a multiple use aquifer), and/or
- Evaluate engineering designs (e.g. phreatic surface in a tailings dam, mine dewatering systems, detailed mitigation designs).

The groundwater “models” that can be used to address any of the uses mentioned above encompass a wide range of model types, from conceptual models that describe how the groundwater system is envisioned to operate, to many varieties of a mathematical model. Mathematical models can include:

- Analytical or numerical models
- Different model dimensions (D): 1D, 2D or 3D models
- Groundwater flow model or groundwater flow & transport models
- Steady-state or transient models
- Equivalent porous media or discrete fracture models, etc.

Further description of model types and the selection process is provided in Section 5.

Selection of model type or, for that matter, the need for modelling, is a function of the perceived risk or potential impact to a VEC, the nature of the groundwater system, and the objectives of a given assessment.

From a simple perspective, if there is no perceived risk to a VEC (or if mitigation measures are used that do not require input from a groundwater model, or are not relevant to groundwater) groundwater modelling is unlikely to be required. Likewise, even if there is a perceived risk, if the results of simple, conservative assumptions suggest impacts are highly unlikely, more complex modelling may not be required. Ultimately, the need for groundwater modelling is a judgment call based on the risk, groundwater conceptual model (and complexity of that model), and the objectives of a given impact assessment.

Assuming that groundwater modelling is determined to be required, regardless of the specific purpose, the following general guidelines should be followed when developing a groundwater model:

- The modelling objective should be clearly defined and stated (as specifically as possible) to determine the necessary data requirements and modelling approach and methods.
- In the context of environmental assessments for proposed resource projects, the modelling objectives should be defined based on the specific issue(s), or VEC of concern.
- The methods and complexity of the modelling exercise should be consistent with the modelling objectives and the required accuracy in model predictions.
- The scope of the modelling study should take into account data availability, available budget, and time constraints while ensuring that the modelling objective(s) are met.

3.4 MODEL COMPLEXITY

Groundwater models (conceptual and mathematical) vary in complexity based on the potential impacts, modelling objectives, hydrogeological framework, and data availability. In these guidelines, “complexity” can be considered to be “the degree to which a model application resembles, or is designed to resemble, the physical hydrogeological system” (MDBC, 2001). Model complexity may relate to, but does not necessarily have to relate to the spatial extent of a model. Model complexity may apply to either or both the conceptual model or the mathematical model, but a simple conceptual model may necessitate a simple mathematical model.

For the purpose of these guidelines, three levels of model complexity are defined:

- Basic – These are Scoping Level Models based on sparse or limited data (e.g., minimal hydraulic conductivity data; few or no hydraulic head data, etc.). These models have conceptual models with broad assumptions and, mathematically, can be analytical, or “basic” numerical models and often include the type of model termed “parametric”. These models are often used to gain an understanding of the parameters to which a given system is most sensitive and which could be the focus for future data collection, or the basis for broad monitoring networks. Regional or catchment scale models based on limited data that are used to provide a general sense of potential groundwater flow directions are of this type.

- Moderate – These are conceptual and numerical models based on a reasonable, though often limited, dataset and having limited calibration. These models may be used to determine the potential range of change or to “bracket” potential effects that may occur due to a given stress. Such models are often used to guide specific data collection programs or more detailed monitoring plan designs, and are often combined with mitigation plans. Moderate complexity models are often used to support EA applications (e.g., predictions of seepage and resulting water quality impacts on VECs) and require detailed sensitivity/uncertainty analysis.

- Complex – These are conceptual and numerical models based on extensive long-term data and/or specific environmental impacts assessment requirements. Data availability is typically high, calibration is rigorous based on induced stresses, and the models are verified. For mining projects, these models are often calibrated to observations collected as the mine is developed. For example, inflows to an open pit or seepage data are used for calibration and integrated with detailed structural geology reviews or mapping.

Model complexity is determined primarily by the modelling objective(s), which may be influenced by data availability, time, budget, and regulatory context. During the initial stage of model planning, the model objectives, approach, and complexity, as well as the limitations or uncertainty related to that approach, should be discussed amongst the proponent and the modeler to be clear on what the model will or will not be capable of. A key aspect to keep in mind is that a numerical model cannot be better than the conceptual model used to formulate it.

For any given objective, model complexity can be reduced but, possibly, resulting in greater uncertainty. The model complexity should be determined in conjunction with the method in which the results will be used. For all types, the model complexity should be consistent with the data available from which to derive model assumptions. Complex models built with limited data are no better than basic models with an appropriate formulation, but are often times more difficult to calibrate and justify. A numerical model cannot be better than the conceptual model used to formulate it.

3.5 MODELLING PROCESS

This section presents an overview of the general groundwater modelling process. Subsequent portions of Section 3, as well as other sections of these guidelines, present further detail on each of the process "steps" that are introduced.

3.5.1 General

Modelling is a multi-phase process progressing through the broad stages of objective definition (which is typically in reference to a VEC), conceptual model development, mathematical model development and analyses, to predictions and uncertainty analysis (see Figure 3-1). Data collection may occur at many points during this progression, but is often required following initial model conceptualization, when a preliminary understanding of the system is being developed. Further data collection efforts may happen at other points in the process, including the calibration and sensitivity step as well as later, following uncertainty analysis. Uncertainty analysis on predictive models may indicate areas or data types that are required to decrease uncertainty.

While the process implies a start and finish, any individual model should not be considered final, but representing a point in time within an overall process of improved conceptualization, review, and refinement.

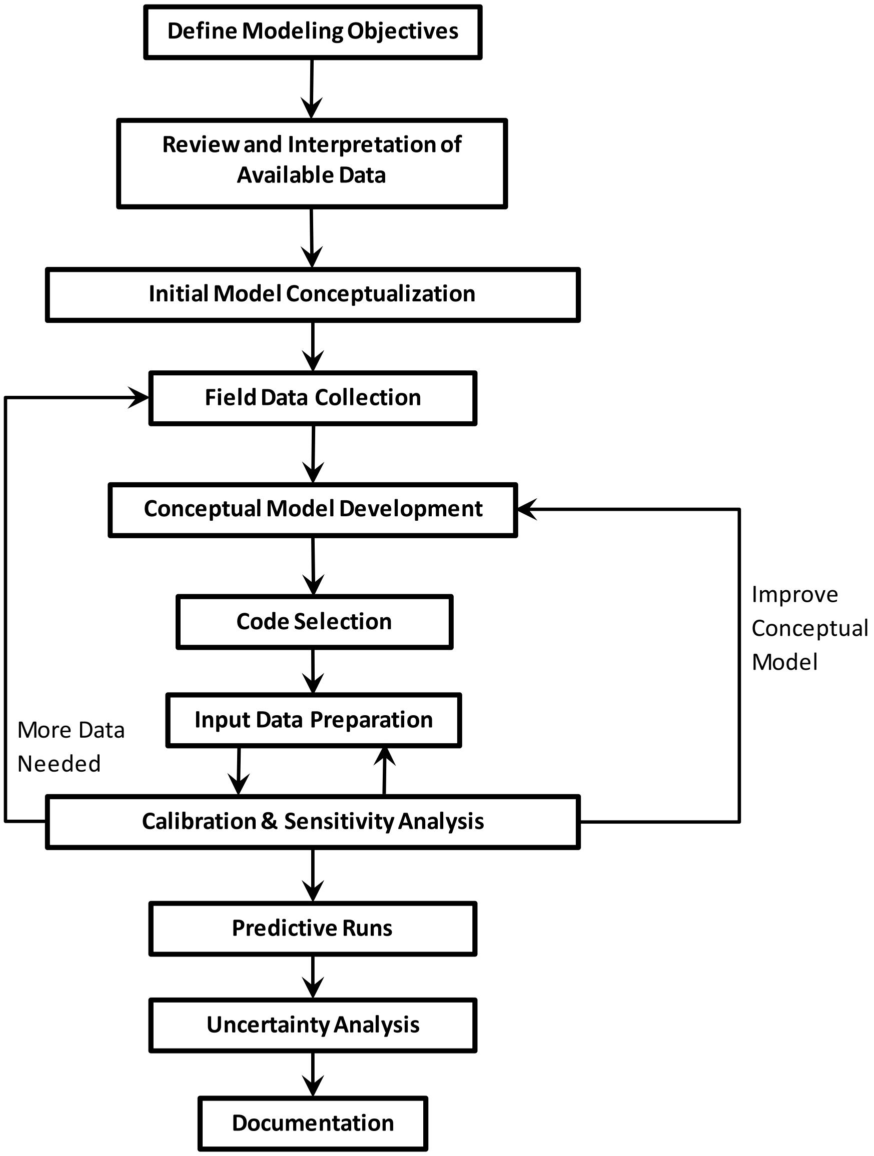


Figure 3-1: Modelling as a multi-phase, iterative process.

3.5.2 Modelling Objective

Determining "What are the model objectives?" is an important first step in the modelling process. Modelling objectives need to be appropriately defined to meet the overall project objectives and need to take into consideration the data availability, budget, and time constraints. Models developed with the objective of assessing environmental effects must have the ecological or environmental receptors defined as well as the nature and scale of effect significance. Models developed for engineering purposes may have objectives defined differently than those for effects assessment. For example, engineering models may be constructed to estimate maximum expected pit wall pore pressures or order of magnitude inflows from groundwater seepage.

Model objectives for natural resource projects may be defined in the context of risk assessments. Framing model uncertainty in relation to risk can often provide guidance to the model objective and the required complexity/accuracy in model predictions. Mitigation plans may be required (or implemented) if the risk of incorrect modelling predictions leads to unacceptable consequence(s). In these cases, model objectives may be defined to support a mitigation concept.

Whatever the objective, it must be clearly defined at the start of the process and should be as specific as possible. The definition of very general modelling objectives such as “determination of the groundwater flow field” or “the assessment of seepage mitigation measures” should be avoided. Instead, the modelling objectives should provide specific targets. For example, the modelling objectives for an EA study may be as follows:

- Predict the future (transient) volumetric flow of seepage from Tailings Impoundment “X” to VEC “Y” during active operation.
- Predict the future contaminant transport from Tailings Impoundment “X” to valued ecosystem component VEC “Y” during active operation and post-closure.
- Predict the reduction in impacted groundwater (and associated contaminant load on VEC “Y”)) in response to alternative seepage mitigation strategies (including drains, interceptor wells).

The definition of specific modelling objectives greatly assist the modeller to select the appropriate modelling approach and model complexity. Examples of model objectives for natural resource extraction projects are presented in Sections 3.6 to 3.8.

3.5.3 Review and Interpretation of Available Data

Compilation and review of available data is the first step in model conceptualization. The data available at the initiation of model development, in light of the model objectives, constitute the basis for model conceptualization and preliminary identification of significant gaps that may require additional field data collection programs.

The initial data review has two broad steps: compilation of existing data, and analysis to improve understanding of fundamental system dynamics.

Compilation of existing data may include:

- Identification and review of pertinent literature, such as reports on the site or regional geology, hydrogeology, hydrology, water management, water use, etc.
- Municipal/local, provincial or federal databases (e.g., Provincial observation well network, water quality, streamflow, climate, pumping wells, etc.).
- Results of previous investigations related to geology, hydrogeology, engineering, etc.
- Baseline data already available for the site (water levels, hydraulic testing, streamflows, climate, etc.).

The existing dataset should be reviewed in comparison to baseline monitoring requirements outlined in the *Interim* Water and Air Baseline Monitoring Guidance Document for Mine Proponents and Operators (MoE, 2011). While baseline monitoring requirements may not perfectly match the given objective, this comparison will provide an opportunity to identify gaps in baseline monitoring or different ways in which baseline data may be utilized.

The dataset should be analyzed to provide initial assumptions on system dynamics and parameter distributions. Analyses should include all components that may be pertinent to the system of interest, such as:

- Spatial distributions and temporal variations in groundwater levels, flow directions, flow rates
- Spatial distribution of hydraulic properties such as hydraulic conductivity or transmissivity and values for aquifers or aquitards of interest; correlation to lithology, geologic structure (i.e., faults) or geotechnical parameters (i.e., fractures)
- Groundwater recharge rates
- Recharge/discharge zonation
- Stream baseflow
- Transport parameters, if appropriate.

This initial data review provides the following two outputs:

- Development of a database and understanding of the database that will form the basis for the conceptual model
- A preliminary identification of significant data gaps requiring field data collection programs.

At this stage, it may be appropriate to review and/or adjust model objectives to better reflect model limitations.

3.5.4 Model Conceptualization

Development of a hydrogeological conceptual model ("conceptual model") is a critical early step in the overall modelling process. A conceptual model is a simplified representation of the essential features of the physical hydrogeological system, and its hydraulic behavior, to an adequate degree of detail (MDBC, 2001) to answer the question or issue at hand.

Conceptualization of the groundwater flow and transport system is an ongoing activity throughout the modelling process. There are two key phases in the modelling process when model conceptualization is critically important (see Figure 3-1):

- Initial model conceptualization (usually based on a desktop review of available data)
- Development of a detailed conceptual model (usually after completion of a site-specific field program that was planned with the modelling objectives in mind).

The initial model conceptualization tends to be more general and has the objective of identifying critical data gaps and the design of a suitable data collection program. The second phase of model conceptualization is more detailed (and quantitative) and is aimed at defining and simplifying the flow and transport problem in such a way that it can be expressed in a mathematical model.

The scope and complexity of a hydrogeological conceptual model should reflect the modelling objectives. The conceptual model must have the necessary detail to achieve model objectives, but model objectives also should not be defined that are beyond the limits or level of detail capable in the conceptual model.

The conceptual model is the basis for the design of a mathematical model; the mathematical model provides a solution to the flow system for the given conceptual model. As such, the conceptual model includes a description of the components that are incorporated into the mathematical model.

The potential for updates to the conceptual model over time as further understanding of the system is gained should be recognized. For example, problems in model calibration may trigger a review and possibly a revision (or update) of the conceptual model (see Figure 3-1). Additional data collection may also result in a revision of the conceptual model (Figure 3-1).

Further guidance on model conceptualization is provided in Section 4.

3.5.5 Field Data Collection

3.5.5.1 Purpose

Field data collection in the modelling process is intended to fill gaps or uncertainties specific to the site or project identified during development of the conceptual model and which are considered necessary to achieving model objectives. These data requirements may differ from or expand upon earlier baseline monitoring requirements as outlined in the *Interim* Water and Air Baseline Monitoring Guidance Document for Mine Proponents and Operators (MoE, 2011), in that the modelling being undertaken may be occurring after submission of an Application for an Environmental Assessment Certificate. Additional information for mining projects may be available, such as updated mine plans or mitigation measures, or potential impacts to VEC's in which groundwater pathways are believed to play a significant role, may be better recognized.

3.5.5.2 Scope of Data Collection

Identification of the requirement for additional data collection should be a fundamental component of the initial data review, conceptual model development, and mathematical model planning. Additional requirements may vary depending on project type, scope and permitting stage but, for this guideline, are specifically considered in terms of mathematical model requirements.

Data collection program requirements identified at this stage in the modelling or permitting process could involve physical groundwater parameters or requirements for transport modelling. In both cases, the additional data requirements may relate more to a specific component of the model objectives or information specifically needed for mathematical modelling itself than have previous data collection programs (by area, potential effect/pathway or regional groundwater question).

3.5.5.3 Types of Field Data

General data inputs specific to completion of a mathematical model as outlined in these guidelines can be categorized into three types:

1. Site characterization (parameters for model input such as stratigraphy, aquifer properties, topography, climate)
2. Groundwater monitoring (parameters to be simulated such as water levels, groundwater discharge)
3. Performance monitoring (parameters predicted by the model such as drawdown, contaminant breakthrough).

At a minimum, type 1 and 2 data are required for mathematical models of any significant complexity, but particularly if numerical modelling is envisioned. Data requirements specific to types 1 and 2 inputs should include:

- Coverage of all areas of potential concern (e.g. WRDs, open pit, tailings storage facility [TSF])

- Coverage of all hydrogeological units of interest
- Good spatial distribution (not all clustered in one small area of the domain)
- Coverage of the entire depth range of interest
- Transient aquifer hydrogeological unit properties (storage) and transient monitoring (if problem is transient).

For mining projects, Type 3 data may be required, for example, for assessments of specific mitigation methods (i.e., groundwater interception systems) or calibration of pit or underground inflows. In these cases, data requirements may include:

- Transient pumping rates and pumping water levels
- Transient water levels from observation networks, and/or
- Streamflow and/or seepage flow monitoring over time.

3.5.5.4 Additional Requirements for Groundwater Extraction

For large (>75 L/s) groundwater extraction projects, pumping tests can be considered a mandatory requirement, but additional data may be required to address specific issues, such as groundwater – surface water interaction or interference with other pumping wells, that may not be sufficiently understood to constrain model uncertainty.

The need for additional data may be identified early enough in this process to justify further work, but also may be a result of the mathematical modelling itself. For groundwater extraction (and mining), the potential for mathematical modelling results to identify additional data needs cannot be ruled out.

3.5.5.5 Data Requirements for Transport Modelling

If transport modelling is to be completed, additional data requirements will exist. Specific data requirements for transport modelling could include:

- Groundwater quality measurements over time
- Location, history and mass loading rate of chemical sources and sinks
- Average groundwater velocities (horizontal and/or vertical)
- Effective porosity
- Soil bulk density
- Soil organic content
- Longitudinal and Transverse dispersivity
- Reactive transport parameters (may require laboratory studies).

In certain cases, data requirements for transport modelling can be directly determined from field data. In other cases, sensitivity analyses based on a plausible range of values or calibration to observations may be the only way to constrain a given parameter. Therefore, the practical benefit of data collection should always be considered in designing a field program. From a modelling point-of-view, any additional data collected should lead to a measurable improvement in model conceptualization and/or the ability to calibrate the model (i.e. reduce model uncertainty).

3.5.6 Selection & Construction of Mathematical Model

Selection and construction of a mathematical model needs to be completed in a manner that is able to meet the modelling objectives, includes relevant aspects of the conceptual model, and is consistent with data available for model calibration.

Selection of a modelling code is required at this point. The modelling code is the computer software that solves the groundwater flow equations. Selection of a modelling code will depend, for example, on the level of assessment required (i.e., simple or complex; analytical or numerical), dimensionality (i.e., 2D plan, 2D cross-section, axisymmetric or 3D) and the required outputs (see Section 5).

Once a code has been selected, model construction can commence. If analytical models are to be used, model construction is relatively simple, involving spreadsheets or a simple model code. If numerical models are used, model construction is more complicated (see Section 6).

Model construction involves converting the conceptual model into a mathematical model. This process entails definition of a model domain or grid and assignment of parameters to each node or grid cell (if numerical). Numerical model construction may require adjustments to the conceptual model, particularly in areas of particular interest, such as a specific VEC (e.g., stream).

Further guidance on model selection and model construction are provided in Sections 5 and 6, respectively.

3.5.7 Model Calibration & Verification

Model calibration and verification is necessary for any predictive model. The ability of a model to simulate observed conditions provides confidence in the conceptual and mathematical model.

Calibration is the process of adjusting parameters or fluxes, such as hydraulic conductivity and recharge, within reasonable limits to match observations. Verification is a process of testing the calibrated model by demonstrating that it can successfully predict a set of observations not used previously for model calibration (see Section 7).

The calibration and verification process can include several iterations:

- Initial review of model calibration and verification: existing data is compared to model calibration and results.
- Data or performance gaps are identified.
- Assuming that data or performance gaps cannot be addressed through reasonable modifications to the conceptual model or plausible (preferably constrained) variations in parameters, make a decision to:
    - Collect more data, or
    - Confirm model verification (at this modelling level) to be able to accomplish the modelling objectives and proceed to predictive scenario simulations

To the extent possible, the model should be calibrated for stresses that the model was developed to predict. For example, a model that is aimed at predicting the influence of a new groundwater extraction project, pumping should be calibrated to a transient data set (preferably a pumping test).

The use of a model calibrated to different hydraulic stresses than those predicted (e.g. use of a steady-state baseline model to predict pit inflow) results in greater uncertainty in model predictions and requires additional sensitivity analyses and/or more conservative assumptions (see below).

A model that is not calibrated should not be used for prediction of environmental impacts. Such a model may be used to illustrate possible outcomes for “what-if” scenarios using sensitivity analyses.

The uncertainty analysis which follows the predictive scenarios should focus, at a minimum, on model sensitivity to model input parameters, but may also focus on model sensitivity to conceptual model changes or alternative conceptual models.

Further guidance on the topic of model calibration and verification is provided in Section 7.

3.5.8 Model Predictions and Uncertainty Analysis

The calibrated baseline model may be used as the basis of a predictive model that is run in order to predict and assess how the groundwater system might change in response to postulated changes in hydrological stresses, model boundaries, or parameters (e.g. inflow in response to pit excavation) (Section 8).

Uncertainty analysis may be undertaken for these reasons:

- Illustrate (and quantify) how conceptual model limitations affect predictive model results
- Quantify the impact of variation in parameter estimates and assumptions
- Provide insight into how model results may be used.

Further guidance on the topic of model predictions and uncertainty analysis is provided in Section 8.

3.5.9 Model Documentation

Documentation should include all aspects of the modelling study from definition of modelling objectives, data review and conceptual modelling, to model setup (including disclosure of key modelling assumptions) and calibration through to model predictions and uncertainty analysis.

Proper documentation of the steps in the modelling process is essential to facilitate a review of the model study and the modelling results. In order for a reviewer to assess the validity (or reasonableness) of the modelling results (often times predictions) the reviewer has to have a good understanding of the whole process that led to these predictions, including the conceptual model, the field data the model is based on and the simplifying assumptions used to construct the mathematical model.

Model documentation is also important for the user (say modeller or proponent) as it facilitates subsequent use of the model, for example when the model is verified and/or recalibrated to new data or used for a different modelling objective.

Further guidance on model documentation is provided in Section 10.

3.6 HARDROCK MINING

This section describes aspects of hardrock mining that may be included in groundwater modelling undertaken at one or more of the phases of mining described in Section 2.

3.6.1 Evaluate Mining Impacts

Predictive groundwater modelling may be undertaken to establish the impact of one or more of the following typical mining activities---for each, a discussion of data needs, modelling accuracy, and use is included:

- Inflow to open pit/underground workings inflow. Estimates may be required to address issues related to the management of discharge from mine dewatering. Level of accuracy (e.g., flow estimates within +/- 50%, 100%, 500%, etc.) can vary depending on available data and what the results are going to be used for; the mathematical modelling approach can be analytical or numerical, depending on the model objectives and required complexity or accuracy Unless large scale pumping tests have been completed, observations of inflow are available from an existing development on site, or from a nearby site, predictions will often focus on uncertainty analyses and a range of possible inflows.

- Aquifer drawdown & loss of groundwater discharge (to surface water). Often combined with inflow predictions, groundwater models may be used to assess potential effects on other nearby groundwater users, or to estimate changes in groundwater baseflow contributions to surface waters. The latter objective is common in BC for mining projects that may affect aquatic habitats. Accuracy of drawdown predictions is typically a function of how well hydraulic conductivity distribution and recharge are understood for the area of interest. In terms of loss of groundwater discharge to surface waters, predictions are often as sensitive to characteristics of surface water-groundwater connections as deeper groundwater conditions (i.e., gaining or losing stream reaches, streambed conductance, magnitude of surface flow vs. change in leakage, etc.). Uncertainty in these predictions is often high because these surface water-groundwater connections are difficult to determine at a detailed level. As a result, effects are often based on conservative assumptions. Catchment-scale water balance approaches with conservative groundwater assumptions may be used in place of groundwater models.

- Groundwater mounding & decrease (or increase) in groundwater discharge (to surface water). Model objectives including predictions of these effects are common for assessment of mine components such as tailings storage facilities or waste rock piles. Accuracy of predictions for proposed facilities is typically related as much to parameters of the tailings or waste rock themselves, and calibration and verification is not possible. As such, focus should be on uncertainty or sensitivity analyses. Mathematical models can be analytical or numerical, and 2D or 3D, depending on characteristics of the facility.

- Seepage & associated contaminant transport from mine waste units. The objective of this type of predictive model is usually to assess the role of groundwater pathways in impacting downstream water quality impacts, from such mine components as waste rock piles, tailings, backfilled and/or flooded pits/underground workings. The required accuracy of predictions will be a function of the magnitude of source terms themselves and sensitivity of the downstream environment to contaminants of concern. The accuracy of predictions will be affected by the understanding of how much load may reach groundwater, the groundwater pathways themselves and engineering design parameters for water management facilities and/or mitigation measures. Mathematical models may be analytical or numerical, but available detail of the conceptual model may dictate what approach is reasonable. Water and load balance approaches using conservative assumptions for groundwater may be used. Numerical models will typically focus on uncertainty analyses and be used to direct mitigation designs. If seepage contaminants are of high concern or VECs highly sensitive, transport models may be required. In such cases, data requirements will be greater and models subject to more extensive uncertainty analyses.

- Effects of post closure slope failures, climate variability (e.g. thawing of permafrost), or other long term factors. Objectives of such predictive models are typically based on potential future scenarios that could affect post-closure site management requirements. Modelling is typically numerical, based on predictive models designed to assess effects or water management requirements during earlier mine phases. As such, uncertainty is high and predictions commonly labeled “what-if” scenarios. Such analyses may result from risk trade-off studies related to factors such as long-term or closure design of tailings or water impoundment facilities and final pit slope angles, bulk-heading of portals for underground developments. Such predictions are often combined with engineering assessments.

3.6.2 Evaluate Engineering Designs or Mitigation Options

Groundwater models may be used to assess the design of water management or mitigation options. In terms of engineering designs, models may be used to assess:

- Dewatering designs (Open Pit, Underground)) – assess scope, requirements and/or effectiveness of a proposed design or design concept.
- Dam seepage – assess or provide input to a proposed design or design concept in terms of potential seepage rate or seepage rate minimization.
- Backfill strategies (underground/open pit) – assess effectiveness or effect of backfilling strategies. Objectives may be to predict how well backfilling minimizes groundwater inflow, the influence of groundwater on flooding of backfilled materials for ML/ARD control, or how groundwater may transport contaminants out of a backfilled area.
- Effects related to surface water management structures – groundwater models may be used to assess effectiveness (or ineffectiveness) of proposed structures. Examples include assessment of effectiveness of groundwater collection using collection ditches, potential leakage from ditches or leakage from constructed ponds.

In terms of evaluation of mitigation options, groundwater modelling can be used to:

- Design requirements for or assess effectiveness of grouting or sealing of fractured bedrock for seepage control.
- Design or assess effectiveness of seepage recovery systems (e.g., wells, drains).
- Design or assess effectiveness of cutoff walls; funnel & gate systems, etc.
- Assess the influence of groundwater flow on bioremediation system effectiveness.
- Provide design input or assessment of passive remediation options (e.g., reactive barriers, natural attenuation, etc.).

As suggested by the wide variety of modelling applications presented in this section, definition of project-specific modelling objectives and the necessary (or appropriate) level of model complexity may be influenced by a large number of factors. The scope of any modelling effort for a hardrock mining project site is likely to be affected by additional complexities. Examples of the potential complexity that may need to be recognized when designing a groundwater model study for a hardrock mining project include:

- Large project scale (often several watersheds and potentially many decades of operation)
- Remote locations (lack of background data and high budget/level of effort for data collection)
- Steep topography
- Complex geology
- Fractured rock hydraulics (fracture flow vs. equivalent porous media – often higher budgets necessary to appropriately characterize heterogeneous, anisotropic fractured systems).
- Hydraulic significance of faults or other significant geologic structures.
- High to extreme aquifer heterogeneity (overburden, bedrock; structures)
- Difficult to quantify groundwater – surface water interaction.
- Additional data requirements necessary to conduct contaminant transport modelling, if necessary.
- Potential for multiple sensitive receiving waters and environments.
- Changing mine designs or mine site conditions during modelling process or over life of mine.

3.7 AGGREGATE MINING

3.7.1 General

This section describes predictive groundwater modelling that may be undertaken for aggregate mines in terms of these guidelines. Predictive modelling is typically focused on assessing potential effects related to proposed operations. As with modelling for hardrock mines, predictive modelling can occur at any time during mine life: the mine planning and approval phase or the active mining or post-closure periods. Predictive models completed as part of the permitting process are often used for initial EA effects assessments. Predictive modelling at later stages in the project is less frequently used, but possible.

3.7.2 Evaluate Mining Impacts

The following are examples of groundwater model studies that may be undertaken for aggregate mines.

- Estimating Inflow to open pit - If the development is expected to intersect the water table, modelling may be required to assess inflow quantities for discharge permits or water management facilities.
- Groundwater – surface water interaction - In a related sense, if the development intersects the water table, modelling may be required to estimate aquifer drawdown and the potential for, or magnitude of, loss of groundwater discharge (to surface water).
- Well Interference (ZOI Analysis) – Again, if the development intersects the water table, modelling may be required to assess the zone of influence (ZOI) related to aquifer drawdown and subsequent effects on other groundwater users.
- Recharge effects: Groundwater recharge may be affected whether or not the development intersects the water table or involves extensive land clearing. Modelling may be required to estimate this effect.
- Assess effects on groundwater quality: Modelling may be used to assess mine-related effects on groundwater quality or offsite migration via groundwater pathways.

3.7.3 Evaluate Engineering Designs

Groundwater models may be used to assess such engineering components as dewatering or water management. Examples include:

- Assess dewatering designs – Groundwater models may be used to design or assess effectiveness of pit dewatering (pumping) schemes.
- Assess mitigation options – In some instances, mitigation may be required to offset potential effects on groundwater. Modelling may be used to assist design of mitigation systems, such as surface water flow augmentation requirements, or to assess mitigation option effectiveness.

As with hardrock mining, groundwater modelling in support of engineering designs is typically completed in conjunction with mine planners or mine engineers. Specific objectives may be quite different than those required for permitting but, if designed appropriately, can be used to address both requirements simultaneously.

3.8 GROUNDWATER EXTRACTION

3.8.1 General

Groundwater extraction projects differ from the previously discussed project types in that extraction of groundwater itself is the objective, rather than something that must be managed or addressed to extract a precious mineral or aggregate commodity.

The hydrogeologic setting for groundwater projects is often significantly different from that for hardrock or aggregate mining projects and is often relatively less complex due to more uniform aquifer type and lack of contaminant transport issues; however, groundwater - surface water interaction(s) can be challenging in the use of groundwater extraction from large aquifers. Also, the presence of multiple groundwater users within a given aquifer may require specific attention.

3.8.2 Baseline Modelling

The baseline conceptual model is important for assessing such factors as the basin water balance, recharge sources and seasonal variability, discharge areas, as well as potential areas of groundwater – surface water interaction. Conceptual model development is a focus at project planning and EA application preparation stages (or equivalent stage for other permits). As with other projects, the conceptual model may be updated at any time, as additional information becomes available. Simple, often analytical or water balance type mathematical models, may be used at the basic to moderate complexity level, to confirm the conceptual model, to assess effects of uncertainty, or better define data collection programs.

3.8.3 Predictive Modelling

Predictions made for groundwater extraction projects typically address a broader range of objectives than other types of natural resource projects. Predictions may not only be necessary to assess potential impacts, but to assess the capacity of an aquifer to support the proposed extraction. Predictions are typically completed to:

- Assess aquifer drawdown - Models may be used to estimate the cone of depression related to an extraction system and assess how it may be affected by varying climate or recharge conditions.

- Assess the potential for well Interference (ZOI Analysis) or effects on other groundwater users.
- Determine the capacity of the aquifer to sustain the proposed extraction. – Basin scale groundwater models or water balance models will be used to assess the sustainability of the proposed extraction.
- Assess loss of groundwater discharge (to surface water). – Models may be used to quantify the effect of groundwater extraction on baseflow contributions to surface water. These effects may have specific implications for aquatic or lentic habitats.
- Assess the potential for saltwater intrusion (coastal areas) – In coastal areas, models may be used to assess the potential for saltwater intrusion (or up-coning) and determine safe extraction rates.
- Determine wellhead protection area (WHPA) – Commonly, large groundwater extractions involve municipalities as the proponent and delineation of well protection areas is a requirement of infrastructure funding grants.

3.8.4 Evaluate Engineering Designs

From the engineering perspective, groundwater models for extraction projects are typically used to:

- Assist in design of extraction wells or well fields.
- Evaluate potential mitigation measures, such as artificial recharge.

3.9 CASE STUDIES USED THROUGHOUT THESE GUIDELINES

To illustrate the use of groundwater modelling for assessment of natural resource projects, three case studies are referenced throughout the guidelines: two hardrock mining projects and one groundwater extraction project. Detailed descriptions of the case studies are presented in Appendix C, while specific components are used as examples throughout these guidelines to illustrate good practice or unique approaches.

These case studies are:

Case Study 1: Open Pit Mine

Conceptual and numerical groundwater models were used to assess a proposed open pit mine in north central B.C. The mine site occupies a valued ecosystem comprising fish-bearing creeks and small lakes hosted in geologic materials indicative of a glacial valley. Key project components will include a two-stage open pit development and a prominent tailings storage facility (TSF).

The conceptual model is presented as well as numerical models used to assess baseline conditions, groundwater flow patterns and groundwater – surface water interaction, make estimates of pit inflow and seepage from the proposed TSF.

This case study illustrates a reasonable approach at this phase in mine planning and impact assessment to understand potential effects of the proposed project on groundwater and make initial decisions in regards to mitigation requirements.

Case Study 2: Underground Mine

Conceptual and numerical groundwater models were used to assess a proposed underground mine in northwestern B.C. Seepage from the Site is considered to have the potential to effect down gradient fish-bearing streams, as well as surface water and groundwater used for drinking water supply. The key project component of interest is the underground workings.

The conceptual model is presented as well as numerical models used to assess groundwater flow directions and quantities, estimates of mine discharge and to assess potential impacts on surface water discharge processes. Reactive and non-reactive transport modelling were used to illustrate potential timing of contaminant breakthrough.

This case study illustrates another reasonable approach at this phase in mine planning and impact assessment to understand potential effects, and presents a thorough uncertainty analysis incorporating multiple conceptual models.

Case Study 3: Groundwater Extraction

Conceptual and numerical groundwater models were used to assess a proposed groundwater extraction project in southwest B.C. Extraction was considered to have the potential to effect residential and municipal groundwater users, surface water flows and lake levels. The key project component is the well field itself.

The conceptual model is presented as well as numerical models used to assess potential effects on the aquifer, other groundwater users and surface water features, and to define the zone of influence.

This case study illustrates a reasonable approach to EA-level assessment of a groundwater extraction project and uncertainties.

SUMMARY POINTS FOR MODELLING FOR IMPACT ASSESSMENT OF NATURAL RESOURCE PROJECTS

1. A groundwater model is a generic term describing the sum of all components used to describe a groundwater system, including a conceptual and mathematical model.
2. Groundwater models are used to address specific questions or objectives, and can vary widely in terms of type and approach depending on the project.
3. The modelling objective should be clearly defined, specifically stated and, for environmental assessments should reflect the specific issues or VEC of concern.
4. Model complexity is a function of the available data, hydrogeologic understanding and the model objectives.
5. Model complexity can range from basic (incorporating broad assumptions or using limited data and relatively simple mathematical methods) to moderate (having a reasonable conceptual model, data for calibration of a numerical model, if necessary, and detailed sensitivity/uncertainty analysis) to complex (numerical models based on extensive site specific data, rigorous calibration and possibly verification). Most EA-level models are of the moderate level of complexity.
6. Modelling is a multi-phase process involving definition of model objectives, review and interpretation of available data, model conceptualization, further field data collection if necessary, selection and construction of a mathematical model, calibration and verification, predictions and uncertainty analysis.
7. Model documentation is important to provide transparency and to facilitate review of the model and its results.
8. Groundwater modelling for natural resource projects can have widely variable objectives depending on project type and should be considered when defining the appropriate approach and complexity.

4 CONCEPTUAL MODEL DEVELOPMENT

4.1 INTRODUCTION

4.1.1 General

The development of a conceptual model is one of the most important aspects of a groundwater modelling study, for the conceptual model is the basis of analytical and numerical models that are formulated to replicate field groundwater conditions.

This section describes the nature and formulation of conceptual models. This section provides an overview of the information and processes that need to be considered in constructing a conceptual model for groundwater flow and contaminant transport models, respectively.

This section also discusses potential errors in the development of a conceptual model which could significantly affect the modelling results and should be avoided.

Anderson and Woessner (1992) provide guidance on the development of conceptual models for groundwater flow modelling. Zheng and Bennett (1995) give useful guidance on developing conceptual models for contaminant transport modelling.

4.1.2 Definition

A conceptual model is a simplified representation of the essential features of the physical hydrogeological system, and its hydraulic behavior.

In scientific terms, a conceptual model is a hypothesis which is formulated on the basis of the available data, experience and the professional judgment of the modeller.

4.1.3 Formulation & Use of the Conceptual Model

The conceptual model is based on an initial literature review, data collation and hydrogeological interpretation. The conceptual model should:

- Reflect the modeller’s concept of the natural system.
- Represent the crucial factors/processes influencing groundwater flow and contaminant transport.
- Include sufficient detail to address the questions and modelling objectives (refer Section 2)
- Enable critical questions to be answered by the examination of the mathematical model based on the conceptual model.

Many simplifying assumptions need to be made partly because a complete reconstruction of the field system is not feasible, and partly because there are rarely sufficient data to completely describe the system in comprehensive detail.

The conceptual model should be developed using the principle of simplicity (or parsimony), i.e., the model should be as simple as possible, while retaining sufficient complexity to: (i) adequately represent the physical elements of the system; (ii) reproduce the system behavior to be studied; and (iii) facilitate answering the questions related to the modelling objectives (MDBC, 2001).

The modeler should avoid over-simplification, which results in a model that is incapable of simulating observed conditions adequately. At the same time, incorporation of too much complexity may result in a non-transparent and unwieldy model which is not suitable to study a relatively simple problem.

Like all hypotheses, the conceptual model has to be tested. This can be done by converting the conceptual model into a mathematical model and calibrating the model against field observations. If the mathematical model cannot be calibrated satisfactorily this may indicate a flaw in the conceptual model and the conceptual model will have to be revisited and modified (see Box 7 in Figure 2-1).

4.1.4 Limitations of Conceptual Models

A conceptual model rarely explains all field observations and the development of the conceptual model must be an iterative process; it should continually be updated as new data become available, as the understanding of the system is improved, or as questions and modelling objectives evolve. In other words, a conceptual model represents a "work-in-progress" which should be continually challenged by the modeller throughout the modelling project.

A conceptual model may be imperfect and may even be wrong because (NGCLC, 2001):

- The information used to define a problem is incomplete
- Incorrect assumptions are made in developing the conceptual model (e.g. can it be assumed that a sand and gravel deposit identified in three investigation boreholes extends laterally below the whole extent of the site, or have three separate sand and gravel lenses been penetrated?)
- The conceptual model ignores key processes influencing the process to be simulated (e.g. irreversible sorption in solute transport is ignored)
- The physical and/or chemical processes occurring are poorly understood.

4.1.5 Documentation

The conceptual model should be described in a stand-alone *Conceptual Model Report* or in a specific section of the *Groundwater Modelling Report.*

The conceptual model should be described in words and supported diagrams, figures, graphs, and tables. The conceptual model is usually presented visually as a series of 2-D cross-sections or as a 3-D block diagram, with supporting text and data tables that describe and quantify the components and features of the model. Examples of visual illustrations supporting conceptual models for different mining projects are shown in Figure 4-1 to 4-4 (see section 4.2).

The data used for development of the conceptual model should be readily available to the reader, either in the C*onceptual Model Report*, in a preceding section of a more comprehensive modelling report, or in a stand-alone document (data report) accessible to the reviewer.

The preparation of plans, contour maps, cross-sections and block diagrams is essential in the development of a conceptual model as it enables others to gain a rapid understanding of the system. Visualization of important aspects of the conceptual model may also highlight data gaps and inconsistencies and provides a method for checking that any assumptions make sense in the light of existing data (NGCLC, 2001).

Simplifications and assumptions should be documented and supporting information provided to justify that assumptions are reasonable. The conceptual model is a simplification of the complexity of field conditions. Hence, conceptual cross-sections and/or block diagrams typically have a greater degree of abstraction than those prepared for detailed field investigations.

In more complex projects, several illustrations will be required to provide a good illustration of the conceptual model. For example, a combination of plan view and cross-section may be needed to adequately illustrate a complex 3D groundwater flow field (see figures 4-3a/b). In projects with a contaminant transport component (e.g. Rum Jungle mine in figures 4-3a/b) separate illustrations may be required for groundwater flow and contaminant transport.

In describing and documenting the conceptual model the following should be included: (NGCLC, 2001):

- What is known and understood about the site. Supporting data, variability, and calculations should be provided
- What is not known or not understood about the site and whether it is thought to be important.
- What are the uncertainties in the data. This should also include a list of further data requirements (“data gaps”) and proposed sampling or investigations to obtain essential information
- What has been assumed about the system. Justifications for decisions and any supporting data or calculations should be provided.
- What has been ignored or simplified in order to answer questions. Justifications for decisions and any supporting data or calculations should be provided.

The following should be documented as part of the documentation supporting the description of the conceptual model:

- Site description and history of resource development (if applicable).
- Hydrology & climate.
- Regional geology, including geological origin and spatial distribution of major bedrock units.
- Site geology, including type and spatial distribution of overburden (sediments), spatial distribution of main lithologies (bedrock); degree and depth of bedrock weathering, description of bedrock quality (geotechnical bedrock logging),
- Structural geology, including presence/alignment of main structures (faults, synclines/anticlines, bedrock contacts etc.) and local and/or regional anisotropy (e.g. from stress analysis, fracture mapping, pumping tests etc.).
- Maps of groundwater elevations and piezometric surfaces and hydrographs of groundwater elevations.

The conceptual model report (or section in a more comprehensive modelling report) should identify critical data gaps and provide recommendations on how to fill those data gaps.

4.2 EXAMPLES OF CONCEPTUAL MODELS

Figures 4-1 to 4-4 provide examples of visual illustrations supporting different conceptual models of groundwater flow and contaminant transport for mining projects.

Figure 4-1 shows the conceptual model for groundwater flow at the historic Mt. Morgan mine site in section, illustrating: (i) main hydrostratigraphic units, (ii) groundwater flow paths, (iii) groundwater discharge to the Dee River and (iii) important geodetic elevations of sources (backfilled pit), seepage collection ponds, and the receptor (Dee River) (Wels et al., 2006).

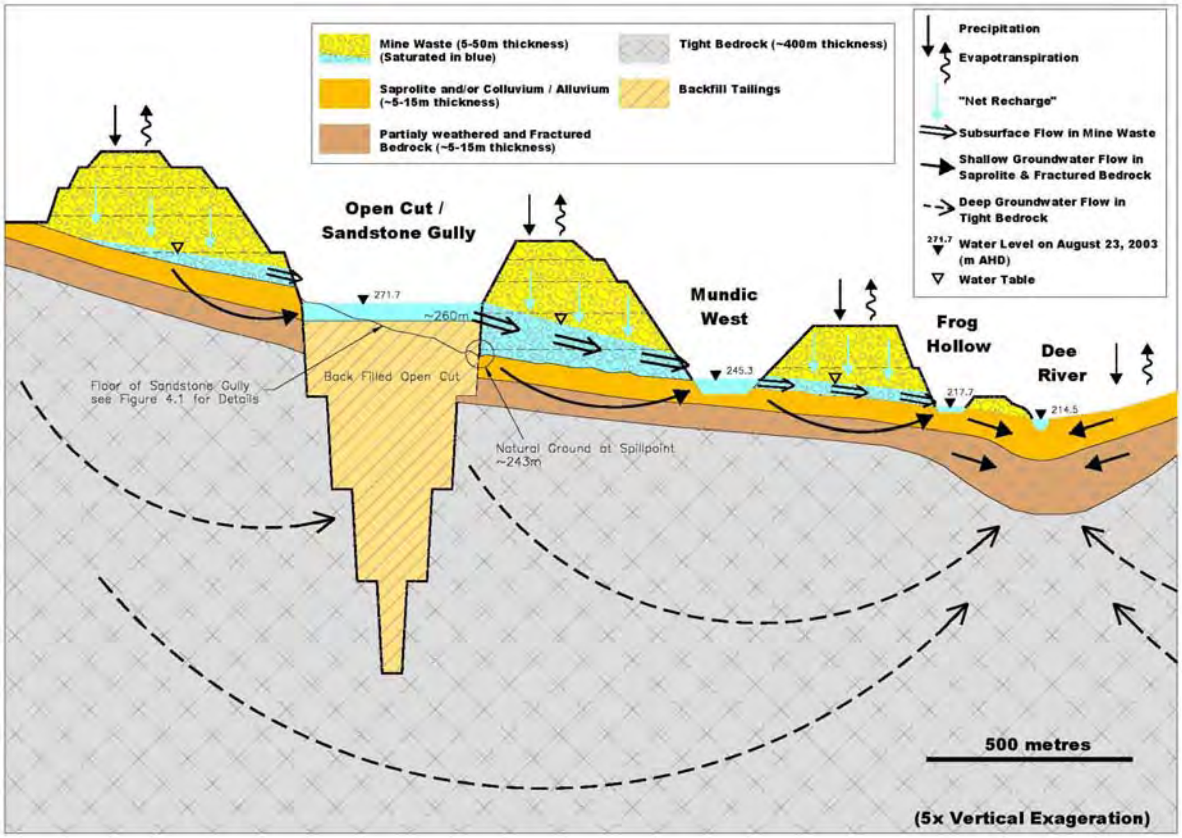


Figure 4-1: Conceptual model for groundwater flow at the historic Mt. Morgan mine site (reproduced from Wels et al., 2006).

Figure 4-2 conceptualizes groundwater flow at a mountainous site in northern B.C. in section, illustrating: (i) recharge and discharge areas, (ii) the main aquifer units, and (iii) major groundwater flow paths. The model also illustrates the presence of a major fault which is conceptualized as a preferred (high K) flow path for groundwater flow to surface.

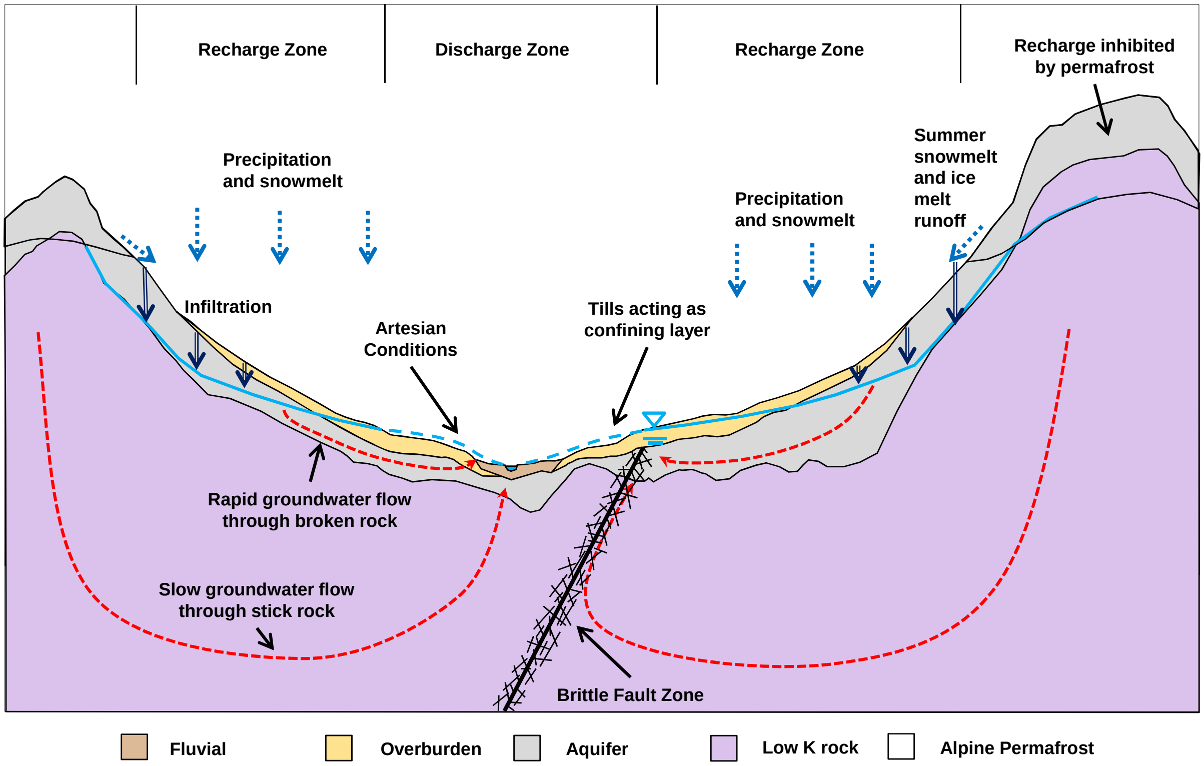


Figure 4-2: Conceptual model for groundwater flow in mountainous terrain in northern British Columbia.

Figure 4-3a/b shows the conceptual flow and transport model for the historic Rum Jungle mine site (Robertson GeoConsultants Inc., 2012). Figure 4-3a shows the direction of groundwater flow and the main sources and pathways of contamination in plan view. Figure 4-3b illustrates the main hydrostratigraphic units in cross-section. Also shown is the range of hydraulic conductivity values for each unit, as determined from site-specific testing at the site.

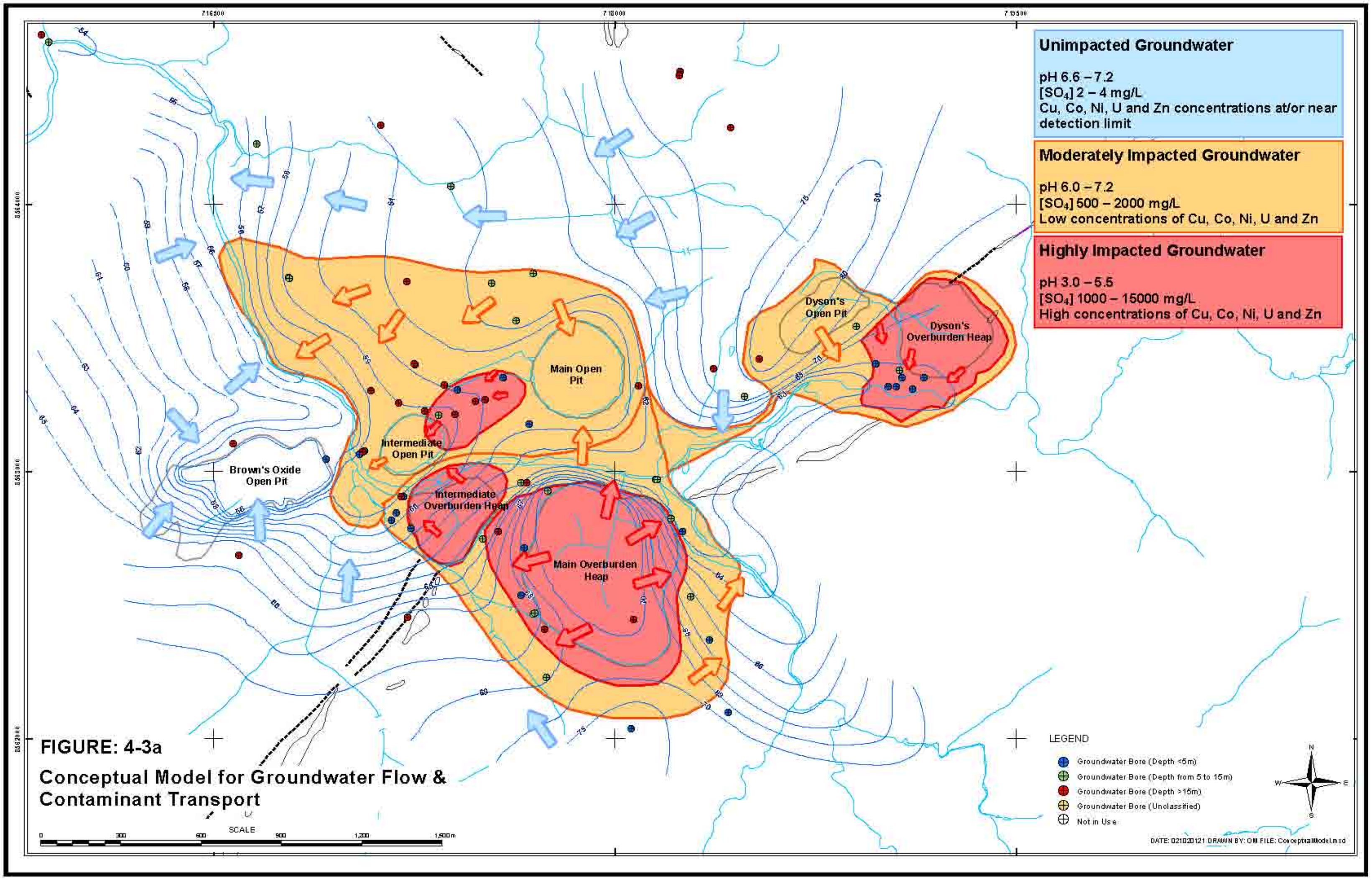


Figure 4-3a: Conceptual model for Groundwater Flow and Contaminant Transport at the Rum Jungle mine site in plan view (Robertson GeoConsultants Inc., 2012).

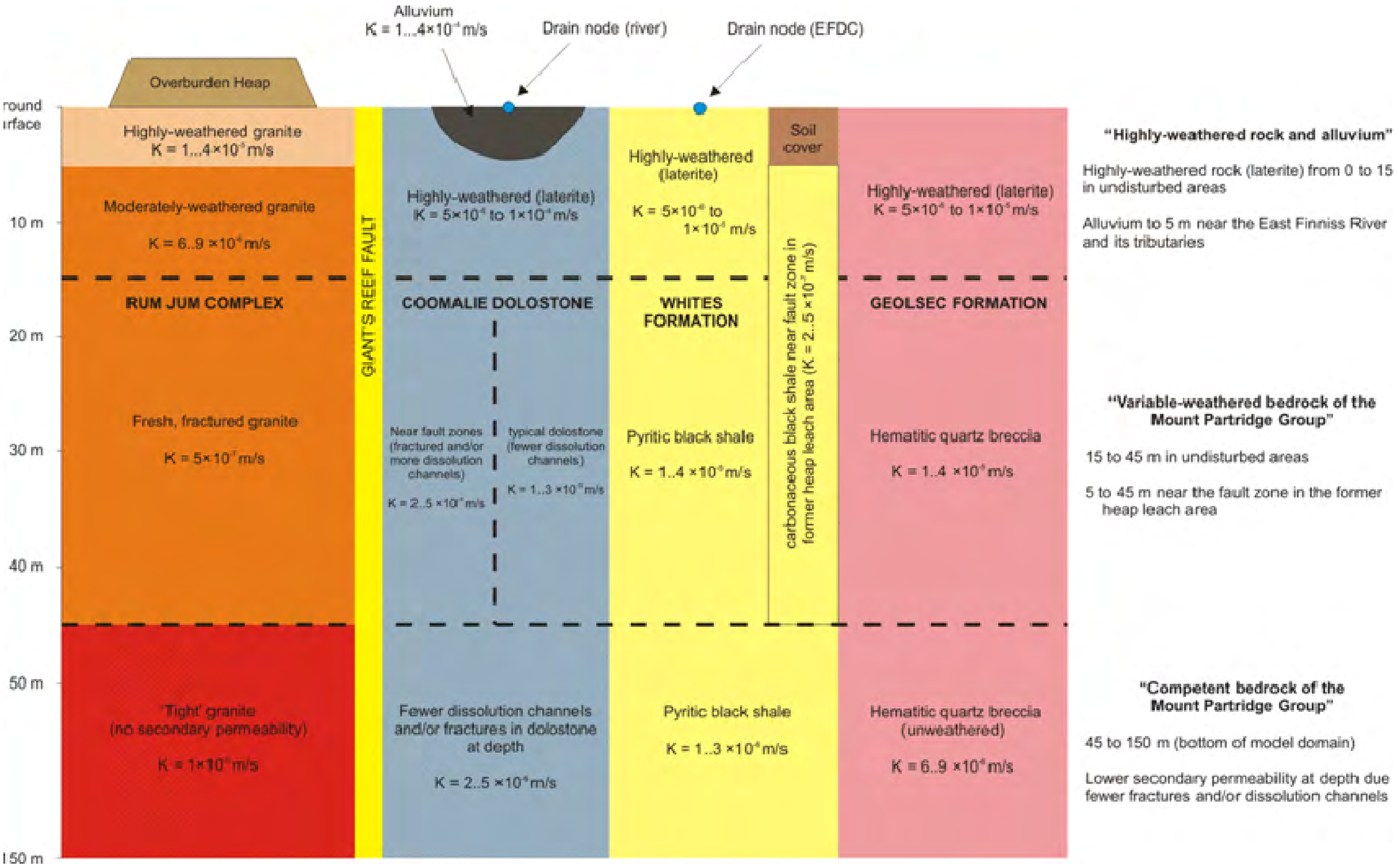


Figure 4-3b: Conceptual model for Rum Jungle mine site showing hydrostratigraphic units in cross-section (Robertson GeoConsultants Inc., 2012).

Figure 4-4 shows a conceptual model of the interaction of groundwater with a flooded pit lake (Bowell, 2002). This conceptual model focuses on the geochemical processes controlling the water quality in the mine pit lake.

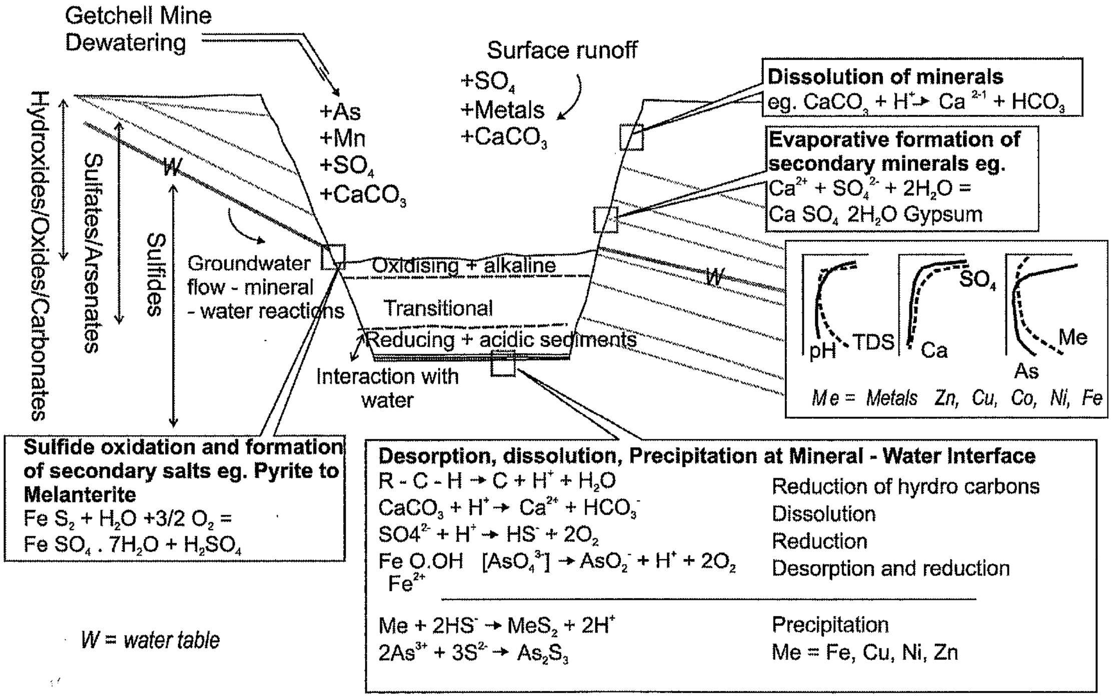


Figure 4-4: Conceptual model illustrating complex relationships between limnological and geochemical controls on pit lake water quality (Reproduced from Bowell et al., 2002).

More details on all four examples are provided in the following sections of conceptual model development.

4.3 CONCEPTUAL MODELS FOR GROUNDWATER FLOW

4.3.1 General

This section summarizes the information and processes that need to be considered for the development of a conceptual groundwater flow model. A comprehensive check list of specific information that should be considered for the conceptual model is provided in Appendix D.

In developing (or reviewing) the conceptual model, the modeller (or reviewer) should ask what evidence there is to support the conceptual model (e.g. head measurements, hydraulic testing), and whether the conceptual model for this project site is plausible compared to experience at nearby sites or sites in similar setting (reference or analogue site).

4.3.2 Hydrogeologic Setting

The extent of data collection and review related to the hydrogeological setting depends on the local site conditions. For example, a proposed groundwater extraction project in a shallow aquifer consisting of fluvio-glacial sediments may require an in-depth review of the geological origin of sediments and seasonal climate conditions while a proposed underground mine in deep bedrock will require a more detailed review of bedrock geology and structural analysis.

At sites with project history (e.g. existing mine sites, brownfield sites and/or groundwater aquifers with past abstractions) a detailed review of past resource development(s) and the resulting response of the aquifer system is a critical component of model conceptualization.

4.3.3 Model Domain

The conceptual model domain must be defined. In most cases, the domain of the conceptual model will be the same as the domain used for numerical models. The conceptual model domain may be larger than the numerical model domain, for example if a project is modeled using several “sub-models” to cover different aspects of a single site (i.e. separate numerical models for an open pit and a TSF).

The size of the model domain depends on the scale of the project (local, intermediate, regional) and the spatial extent of anticipated impacts. Common model domains used for groundwater modelling in large groundwater resource projects include:

- “Aquifer” model, which uses the known (or inferred) spatial extent of the main aquifer of interest to define the model domain
- “Watershed” model, which uses the watershed (or sub-watershed) in which the project is located as a convenient model domain,
- “Local” model, which defines the model domain based on the specific project component(s) to be studied (e.g. an open pit or a tailings impoundment)

The watershed model is the *de facto* default model for many natural resource projects. However, this model domain may not always be the appropriate model domain. For example, the scale of a watershed (or even sub-watershed) model may be too large to adequately model a local groundwater flow or contaminant transport problem. A watershed model with a size of >100 km^2 usually does not have the spatial resolution to predict contaminant concentrations in groundwater discharging in specific salmon spawning areas. The conceptual model documentation should justify the scale of the model domain and discuss the potential implications for scale-dependent modelling results (e.g. contaminant transport).

4.3.4 Model Boundaries

The conceptual model documentation should justify the selection of boundaries. The most common boundaries used for groundwater modelling in the larger groundwater resource projects include:

- Watershed divide (representing lines of flow divergence)
- Streams and/or valley centers (representing lines of flow convergence)
- Large water bodies such ocean, lakes, rivers (representing areas with constant and/or known hydraulic head)
- Geological boundaries such as bedrock contact or faults (representing large-scale features of known or assumed hydraulic behavior)
- No-flow conditions perpendicular to streamlines

The conceptual model documentation should identify the monitoring data (or other field evidence) used to select a certain boundary condition. If no data or observations are available, the rationale should be given for the assumed model boundary and the implications of the assumption on modelling results.

The conceptual model documentation should discuss potential changes in the model boundary condition(s) over time due to natural variations (seasonal flow field, climate change) and/or project development. For example, the use of a no-flow boundary to represent a surface watershed divide may be adequate for current conditions but may not be correct for modelling of a large open pit (or underground development) which can result in significant drawdown (cone of depression) reaching hundreds of meters (or even kilometers) beyond watershed divides. In this case the model boundaries would have to be set at sufficient distance such that current and future stresses can be modeled without artificial boundary effects (see case study in Appendix C2 for such an example).

4.3.5 Hydrostratigraphic Units and Hydraulic Properties

The conceptual model formulation should include consideration of (and the report should describe) the presence and spatial distribution of major hydrostratigraphic units and their hydraulic properties. Hydrostratigraphic units are a specific geological material (or a group of materials) that has sufficiently similar hydraulic properties that they can be considered a hydraulic unit for the purpose of a hydrogeological study.

In more complex settings the spatial distribution of hydrostratigraphic units should be visualized using cross-sections and/or 3D block diagrams (e.g. see figures 4-1 and 4-2).

A conceptual model should subdivide the main hydrostratigraphic units at a site into: main aquifer units (i.e. where most groundwater flow occurs); aquitards (with limited groundwater flow); and aquicludes (with insignificant groundwater flow). The selection of hydrostratigraphic units must be justified and documented. If different units are lumped together (e.g. due to lack of data and/or model convenience) provide justification.

The conceptual model should include consideration of (and the report should describe) the hydraulic properties of major hydrostratigraphic units, including, if applicable:

- Hydraulic conductivity (K)

- Storage parameters specific yield (Sy)
- Specific storage (Ss and effective porosity (n_{eff}).

The conceptual model formulation should include consideration of (and the report should describe) how properties are determined for each unit. Preferably, hydraulic properties selected in the conceptual model should be based on site-specific hydraulic testing. The conceptual model formulation should include consideration of (and the report should describe) the source and uncertainty of available field data and, to the extent possible, provide summary statistics of the various hydraulic properties.

At complex sites, a visual representation of the available field data used for the conceptual model is recommended (e.g. scatter plot of K versus depth; histogram of K statistics by bedrock lithology).

Natural porous media and fractured rock have significant "heterogeneity" (variability in space) and "anisotropy" (variability with direction) of aquifer hydraulic conductivity and other properties. The conceptual model should include consideration of (and the report should describe) the heterogeneity and anisotropy of the main hydrostratigraphic units of the model which are defined as follows:

- **Heterogeneity** is the variation of key parameters such as hydraulic conductivity within a hydrostratigraphic unit. A heterogeneous unit has a large range of hydraulic conductivity with no discernible spatial pattern (e.g. a debris flow or moderately fractured bedrock). The degree of heterogeneity is scale-dependent; it has a strong effect on small-scale flow paths and interactions with sources and sinks and boundary conditions. In fractured bedrock, flow occurs mostly in fractures and not in the unfractured matrix, thus the heterogeneity of fractured rock aquifer refers to variation in fracture properties and interconnectivity.

- **Anisotropy** is the preferred spatial orientation of hydraulic conductivity and resulting preferred direction of flow within a material. Examples of anisotropy include permeable bedding planes within sediments, or preferred orientation of permeable interconnected fractures in rock. The degree of anisotropy must be defined in the conceptual model, and will likely be adjusted in mathematical model calibration.

Strong anisotropy should not be introduced into the model if not clearly supported by geologic data. The conceptual model documentation should discuss evidence of heterogeneity and anisotropy in the field data (or lack thereof) and explain how heterogeneity and/or anisotropy are accounted for in the model. If heterogeneity and/or anisotropy are not accounted for in the conceptual model, this should be justified and potential implications for modelling results should be discussed in the model documentation.

4.3.6 Groundwater Recharge

Recharge is defined as the downward flow of water reaching the water table, adding to groundwater storage (Healy, 2010). Groundwater recharge occurs through diffuse and focused mechanisms (see Figure 4-5). "Diffuse recharge" is distributed over large areas in response to precipitation infiltrating the soil surface and percolating through the unsaturated zone to the water table (Healy, 2010). Diffuse recharge is also referred to as local recharge or direct recharge. "Focused recharge" is the movement from surface water bodies, such as streams, canals, or lakes to an underlying aquifer. Focused recharge is also referred to as indirect recharge or leakage.

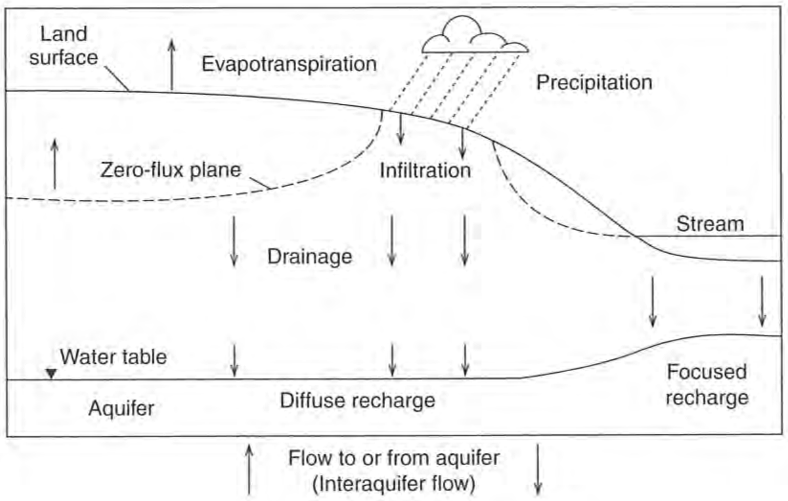


Figure 4-5: Vertical cross-section showing infiltration, drainage, aquifer recharge, and inter-aquifer flow (Reproduced from Healy, 2010).

Figure 4-2 illustrates different sources of diffuse recharge that were included in the conceptual model for a mountainous site in northern B.C., including precipitation and snowmelt runoff from the mountain sides and summer snowmelt/ice melt runoff from a glacier.

Natural resource projects typically include "artificial recharge" (also referred to as "anthropogenic recharge") such as seepage from flooded open pits or underground workings, mine waste facilities (e.g. tailings impoundments, mine rock piles, storage dams etc.), recharge from land application areas, and/or recharge from injection wells.

Figure 4-1 shows an example of artificial recharge from a flooded open cut at the Mt Morgan mine site which was partially backfilled with reprocessed tailings. A detailed analysis of water levels and water quality indicated that the contaminated groundwater stored in the backfilled open pit was a major source of seepage to the downgradient aquifer system. This artificial recharge represented a major aspect of the conceptual model for the Mt Morgan mine site.

Recharge is usually expressed as a volumetric flow, in terms of volume per unit time (L^3/T), such as m^3/d, or as a flux, in terms of volume per unit surface area per unit time (L/T), such as mm/yr. These guidelines recommend that diffuse recharge values be described in terms of flux (in mm/yr) to allow a direct comparison to precipitation data. In the context of water balance (see below) recharge should be described in terms of volumetric flow (in m^3/day).

Recharge from precipitation is the primary inflow to groundwater systems in many parts of British Columbia and therefore requires careful consideration in formulating a conceptual model. The conceptual model should account for the seasonal behavior of precipitation (i.e. snowmelt and rainfall) and evapotranspiration and how these seasonal variations influence groundwater recharge. A visual comparison of observed seasonal variations in groundwater levels with daily or monthly precipitation data (and snowmelt data for sites with significant snowpack accumulation) over a period of at least one year is recommended for this analysis.

When formulating a conceptual model, the following factors that may influence recharge from precipitation, should be considered:

- Slope
- Ground conditions
- Vegetation
- The spatial distribution of recharge
- The influence of slope aspect, forest cover, elevation, etc. on snowmelt.

Recharge cannot be measured directly and must be estimated. Healy (2010) provides a comprehensive review of the different methods available for estimating recharge. The most widely used methods for estimating recharge include:

- Water-budget methods
- Water table fluctuation (WTF) method
- Baseflow analysis
- Chloride mass balance (CMB) method.

The method(s) most suitable for estimating recharge for a given project depend on local site conditions and available data. Consult Healy (2010) to determine the most suitable method of estimating recharge for a given project. This book also provides a good discussion of the assumptions and limitations of the various methods.

Recharge from precipitation is often one of the greatest uncertainties in groundwater modelling studies. These guidelines recommend that different techniques be used to estimate groundwater recharge due to precipitation. This will provide a measure of the uncertainty in recharge estimate(s). This uncertainty in recharge will have to be evaluated further during mathematical model calibration and sensitivity analysis (see Section 6).

Formulation of the conceptual model should include consideration of the presence, magnitude, and duration of any “artificial recharge” events observed/anticipated in the past, present and/or in the future life of the project. Recharge estimates should be documented (in the conceptual model report) for major artificial recharge processes known to be active (or anticipated in the future) at the site. The recharge flux in waste rock piles, tailings, or other artificial covered and uncovered materials must be estimated (typically independently of the groundwater model) or measured directly to allow proper simulation of local flow conditions and response to stresses.

Focused recharge from surface waters (e.g. streams, lakes etc.) can also be an important recharge mechanism to groundwater, in particular, in drier parts of British Columbia. Recharge from surface water(s) is also referred to as “leakage” in the context of groundwater modelling and is discussed further in the section on groundwater-surface water interaction (see below).

4.3.7 Groundwater Flow Regime

The conceptual model should represent and the supporting documentation should provide a qualitative and pictorial description of the groundwater flow regime, including:

- The main direction(s) of groundwater flow, including a description of groundwater flow from the main recharge areas to the main discharge areas (including major internal sinks such as pumping wells).
- The location of the groundwater table (depth to water) and flow field (water table map for unconfined aquifers and potentiometric map for confined conditions.
- The horizontal and vertical hydraulic gradients in different parts of the aquifer.
- Estimates of travel times/residence times of groundwater (using Darcy calculations).
- Conceptualization of groundwater flow through the various hydrostratigraphic units (which units carry the majority of flow, which units impede flow etc.)
- Variations in groundwater levels over time (e.g. seasonal or ongoing abstraction).

Figure 4-3a illustrates the groundwater flow regime for the historic Rum Jungle mine site (Robertson GeoConsultants Inc., 2011). At this abandoned mine site, the groundwater flow regime is strongly influenced by seepage from the “Main Heap” which has resulted in local mounding of the groundwater table. Seepage from this and other heaps flows towards the East Finnis River which runs through the site. Note that the groundwater flow regime is also influenced by the flooded open pits which intersect the bedrock aquifer.

The conceptual model documentation should describe observed temporal trends in groundwater levels (preferably by using time trend plots) and discuss the cause(s) for these trends. The conceptual model documentation should discuss whether the groundwater flow field can be considered in a dynamic steady-state or whether transient aspects have to be considered. If a steady-state conceptual model is recommended, the limitations and implications for this simplifying assumption should be discussed (see section 5.2.2 for more detail).

4.3.8 Groundwater Discharge

In formulating the conceptual model, the following groundwater discharges should be considered (and documented):

- Seeps and springs discharging to ground surface
- Groundwater discharge into surface waters (lakes, streams)
- Groundwater abstraction (pumping)
- Seepage interception systems (drains, interception wells)
- Inflow to open pit and/or mine workings
- Evapotranspiration (ET).

Groundwater discharge can be measured either directly (e.g. using flow meters, seepage meters, seep surveys etc.) or indirectly (using observed hydraulic gradients and/or water quality).

Figure 4-1 shows an example of an abandoned mine site where groundwater discharge was an important aspect of the conceptual model. The conceptual model for this site included (i) discharge of highly contaminated seepage from an upgradient mine waste pile into a flooded open pit, (ii) discharge of highly contaminated seepage into several sumps (seepage interception) and (iii) discharge of impacted groundwater to the receiving environment (Dee River).

Groundwater discharge is usually expressed as a volumetric flow, in terms of volume per unit time (L^3/T), such as m^3/d. These guidelines recommend that groundwater discharge be described in terms of volumetric flows (in m^3/d). ET should be expressed in terms of unit flux (in mm/yr), to allow direct comparison with climate data, except in discussions of water balance (see below) where ET should be described in terms of volumetric flow (in m^3/day).

The conceptual model documentation should identify the main groundwater discharge processes in the study area, describe their seasonal behavior and discuss the factors influencing groundwater discharge. To the extent possible, the various groundwater discharge components should be quantified using actual measurements (preferred) or estimates.

Groundwater discharge to surface waters is of special concern in the context of groundwater resource projects (as a potential pathway for contaminants). This groundwater discharge mechanism is described in more detail in Section 4.3.9 on groundwater-surface water interaction (see below).

Evapotranspiration (ET) can be an important groundwater “discharge” mechanism, in particular in warmer and drier climates which exhibit a net negative water balance (i.e. ET >> precipitation). Evapotranspiration is defined as the removal of water by the combined effects of direct evaporation from the ground surface and transpiration by plants from the underlying root zone. ET is only active in the root zone which is usually limited to the upper 1 to 5 meters. In groundwater recharge areas (e.g. high elevation areas, hill sides) the groundwater table is typically below the root zone and ET is commonly accounted for implicitly (i.e. by adjusting recharge). In groundwater discharge areas (e.g. stream valleys, wetlands), the groundwater table is close to surface and the influence of ET on the groundwater budget can be significant and may have to be accounted for explicitly.

4.3.9 Groundwater – Surface Water Interaction

Groundwater-surface water interaction is a critical aspect in the assessment of the environmental impacts of proposed groundwater resource projects. Exchange of groundwater and surface water occurs in most watersheds and is governed by the difference between water-table and surface water elevations (Winter et al., 1998) and geology. If the water table is higher than stream water level, groundwater discharges to the stream and the stream is referred to as a “gaining stream” (Figure 4-6a). If stream water level is higher than the water table, the stream is a “losing stream” and surface water flows into the subsurface (Figure 4-6b). If the water table is below the bottom of the streambed the stream is disconnected (or “perched”) (Figure 4-6c).

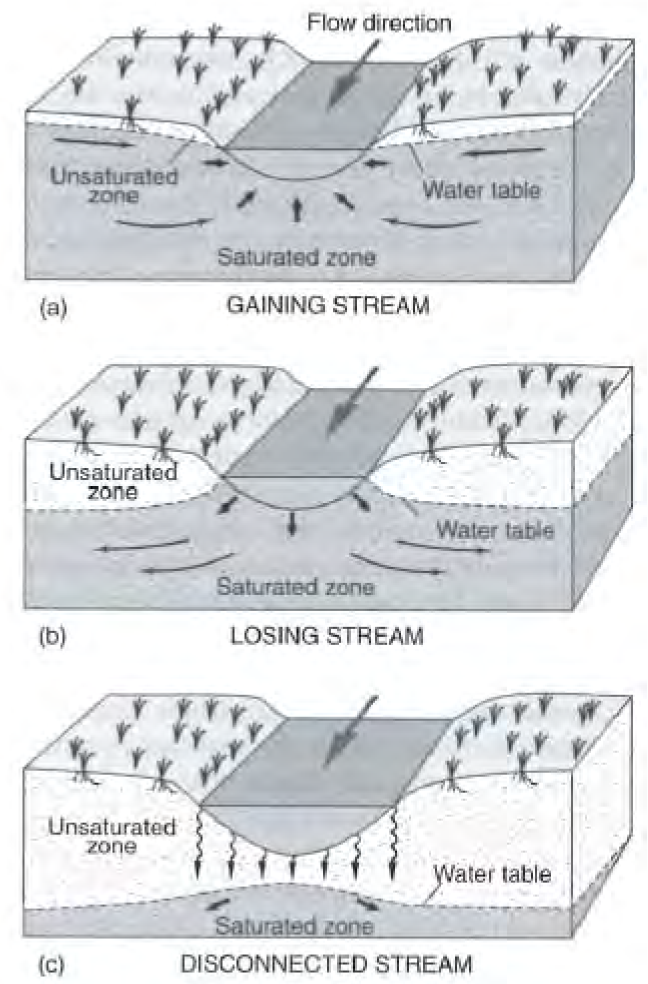


Figure 4-6: Schematic showing (a) gaining stream, stream stage is below water table; (b) losing stream, stream stage is above water table; and (c) losing stream disconnected from aquifer (Reproduced from Winter et al., 1998).

At a regional scale, losing streams are commonly found in arid or semi-arid climates whereas gaining streams are commonly observed in humid regions. Streams in any climatic setting can have reaches that gain and reaches that lose stream water, depending on surface topography and subsurface geological conditions (see Wei et al, 2010 for an example of the Kettle River at Grand Forks as a stream with reaches that are losing and reaches that are gaining). Streams are dynamic and groundwater-surface water interactions tend to be strongly influenced by seasonal runoff and even individual storm events. Interaction of groundwater with lakes tends to be less dynamic but can also show distinct seasonal patterns.

For those projects where a stream (or lake) has been identified as a VEC, a detailed review of the stream (lake) morphology, hydraulic gradients, stream flow and stream water quality is required to determine the groundwater-surface water interaction.

The conceptual model documentation should discuss the main aspects of groundwater-surface water interaction, with special emphasis on streams and/or lakes which have been identified as high VECs. This discussion should include:

- Description of the nature of the interaction (i.e. losing and/or gaining stream/lake).
- Identification of the main reaches where groundwater discharges to surface water (i.e. gaining reaches).
- Estimation of groundwater recharge (from streams/lakes) and groundwater discharge (to streams/lakes).
- Discussion of transient aspects of groundwater-surface water interaction (seasonal variations, storm events).
- Discussion of quantity/quality of monitoring data.

Remaining uncertainties in groundwater-surface water interaction and their implications for the modelling objectives should be discussed in the conceptual model reports.

4.3.10 Groundwater Budget

A groundwater budget is commonly a fundamental component of the conceptual model of a groundwater system. A groundwater budget provides a quantitative link between the different aspects of the conceptual flow model, i.e. groundwater recharge (inflow), groundwater flow across different hydrostratigraphic units, and groundwater discharge (outflow).

A groundwater budget should be compiled as part of conceptual model development. The groundwater budget should include the specified domain of the conceptual model (see above) and should provide estimates for the following water budget components:

- Groundwater Inflows:
    - Groundwater inflow from upgradient boundary (“underflow”)
    - Recharge from precipitation
    - Artificial recharge (irrigation, injection, seepage)
- Groundwater Outflows:
    - Groundwater discharge to surface (seeps and springs)
    - Groundwater discharge to mine units
    - Groundwater abstraction (pumping)
    - Evapotranspiration (in groundwater discharge areas)
    - Groundwater outflow at downgradient boundary (“underflow”).

The groundwater budget is used to identify a plausible range of flows based on available data and professional judgment. The emphasis of the water budget is not on providing a “closed” water balance with a single estimate for each component (which would imply a greater precision than can be achieved at the conceptual level). Instead, a range of flow estimates should be provided in the groundwater budget for each water budget component that reflects the general uncertainty in a given estimate.

Table 4-1 provides an example of a groundwater budget which was developed for the conceptual model of the Rum Jungle mine site (see Figure 4-3a/b). This conceptual groundwater balance provides estimates of low and a high groundwater flows considering the range (and uncertainty) in both recharge (from precipitation and hydraulic conductivity of the main aquifer units.

Table 4-1: Conceptual groundwater budget for Rum Jungle mine site (Robertson GeoConsultants Inc., 2012).

	Flow, L/s		
Component	**Lower**	**Upper**	**Description**
Inflows			
Recharge by rainfall (undisturbed areas)	46	93	Assuming 1500 mm rainfall and percentage recharge rates from text
Recharge by rainfall (mine waste units)	6	12	Assuming 1500 mm rainfall and 25 to 50% recharge to mine waste units
Flows from the Main Open Pit	1	9	Assuming dry season gradients, 45 m aquifer thickness, and K values from Figure 4-3b
From the Intermediate Open Pit	2	15	Assuming dry season gradients, 45 m aquifer thickness, and K values from Figure 4-3b
Total:	56	129	
Outflows (groundwater discharge)			
To the Main Open Pit	1	9	Assuming wet season gradients, 45 m aquifer thickness, and K values from Figure 4-3b
To the Intermediate Open Pit	1	4	Assuming wet season gradients, 45 m aquifer thickness, and K values from Figure 4-3b
To the Browns Oxide Open Pit	5	25	Best judgement from previous model results and preliminary water level surveys
To the upper EBFR	6	9	Assuming wet season gradients, 45 m aquifer thickness, and K values from Figure 4-3b
To Fitch Creek	1	2	Assuming wet season gradients, 45 m aquifer thickness, and K values from Figure 4-3b
To the EFDC	2	9	Assuming wet season gradients, 15 m aquifer thickness, and K values from Figure 4-3b
To the EBFR d/s of gauge GS8150200	7	43	Assuming wet season gradients, 45 m aquifer thickness, and K values from Figure 4-3b
Total:	23	101	
Note: Flows to the flooded Open Pits and tributaries of the East Branch of the Finniss River were estimated via Darcy flow calculations			

In most cases, a steady-state water budget is adequate for a conceptual model formulation or report documentation. A transient water budget (which accounts for transient changes in inflows/outflows and storage) is only required at the conceptual modelling stage when a transient aspect of groundwater flow is the focus of the modelling study (e.g., how would baseflow in a river change over time due to proposed pumping of the new municipal well?).

For mining projects, a water balance is typically an important component of the mine planning process. The mine water balance is usually prepared by a hydrologist and its focus is often surface water. Nevertheless, the mine water balance may provide valuable information to assist in developing a groundwater budget (e.g. recharge estimates). The groundwater modeller (and reviewer) should ensure that the mine water balance and groundwater budget are compatible (i.e. use the same assumptions for processes included in both).

4.4 CONCEPTUAL MODEL FOR CONTAMINANT TRANSPORT

4.4.1 General

For those natural resource projects which require consideration of contaminant transport a conceptual model that includes a model (representation) of contaminant transport is required. A conceptual contaminant transport model is the basis for making the decision on whether a numerical model is required or whether a simplified assessment of contaminant transport (e.g. particle tracking, analytical model or simple mass balance modelling) is adequate. It follows, that a conceptual model of contaminant transport should be developed even if contaminant transport is ultimately not modeled using a numerical transport model.

A conceptual model of contaminant transport should be consistent with the conceptual model of groundwater flow. For example, seepage from a tailings dam that introduces a contaminant to the aquifer should be included as a source of recharge in the conceptual groundwater flow model. Similarly, any seepage interception (e.g. recovery wells, collection drains) should be included in the conceptual groundwater flow model as groundwater discharge.

Although there are many similarities, it is convenient to distinguish between a conceptual model for groundwater flow and a conceptual model for contaminant transport. As defined here, the conceptual model for contaminant transport focuses on the transport aspects of the problem and complements the conceptual model of groundwater flow.

This section summarizes the information and processes that need to be considered in formulating and developing a conceptual contaminant transport model. A check list of specific information that should be considered for the conceptual model is provided in Appendix D.

In developing (or reviewing) the conceptual model, the modeller (or reviewer) should ask what evidence there is to support the conceptual model features (e.g. geochemical controls), and whether the conceptual model for this project site is plausible compared to experience at nearby sites or sites in similar setting (reference or analogue site).

4.4.2 Vulnerability Assessment

The first step in the development of a conceptual contaminant transport model is to determine whether there is a potential for an impact due to contaminant transport. This process is also referred to as "vulnerability assessment" and involves three steps:

1. Identify VECs which are located downgradient of the proposed project site (e.g. fish-bearing streams/lakes and/or drinking water wells).
2. Determine whether the proposed project has the potential to release contaminants of concern (CoCs) to groundwater which may exceed applicable standards.
3. Determine whether any CoC(s) has the potential to reach (via a groundwater pathway) identified VECs.

The last step is also referred to as "pathway analysis". The pathway analysis requires a review of existing data (or the conceptual model) of the groundwater flow regime to determine whether there is a groundwater pathway from the identified source to the identified VEC. The travel time and/or attenuation mechanisms (e.g. dilution, dispersion, degradation) are not considered at this screening level assessment.

If these conditions are met, a conceptual model for contaminant transport is required. In principal, all potential CoCs should be included in the conceptual contaminant transport model. In many cases, the conceptual model (and subsequent numerical transport model) is first developed for the CoC most likely to exceed an applicable standard or guideline (often a conservative solute such as sulphate). The transport results for this CoC are then used to infer the fate and transport of other CoCs (often making conservative assumptions to simplify the analysis).

The conceptual model documentation should describe the key findings of this vulnerability assessment, including a graphical representation (plan view and cross-section) of the location of the potential source(s) of CoCs and the VECs at risk and the potential groundwater pathways along which the CoCs may reach the VECs.

Figure 4-3a provides a simplified conceptual model of contaminant transport for the abandoned Rum Jungle mine site. This figure illustrates the main sources of contaminants and provides a summary of the key CoCs and their observed concentration ranges.

4.4.3 Source(s) of CoCs

Once potential CoCs and a potential impact to VEC(s) have been identified, the past, current and potential future source term(s) of the CoCs in question need to be defined, including:

- The nature and spatial extent of the source area (e.g. mine rock pile, tailings impoundment, heap leach pile, pit lake, backfilled underground mine, backfilled open pit etc.)
- The time history of CoC release:
  - The CoC concentrations as a function of time
  - The CoC mass (i.e. concentration x flow) as a function of time.
- Any geochemical controls on the CoC release from the source (e.g. redox conditions, precipitation/dissolution etc.)
- Any hydraulic controls on the CoC release from the source (e.g. covers and/or liners controlling seepage).

At a brownfield site with existing contamination, the definition of a source term is initially based on a review of relevant site history (including historical maps, plans and records) and available site characterization data, in particular plume delineation (see figure 4-3a). At a proposed new project site, the definition of a source term is primarily based on the project description (e.g. proposed future mine plan(s) and predicted source terms (based on hydrological and geochemical testing and modelling).

The determination of appropriate source terms is a critical step in formulating a conceptual transport model. The uncertainty in source term predictions (in particular for complex mining projects) can be significantly greater than uncertainty in groundwater flow and requires extensive geochemical test work. Unless good field data are available (e.g. at brownfield sites with existing contaminant plumes) significant uncertainty about the source terms remains even after extensive testing. Uncertainty should be discussed and quantified in the conceptual model documentation. In many cases, conservative assumptions have to be made about the source terms in order to test the resilience of the receiving environment and to safeguard against remaining uncertainty.

4.4.4 Applicable Transport Processes

The conceptual model documentation should describe the applicable transport processes for the CoCs including:

- Conservative transport processes
  - Advection
  - Dispersion and
  - Dilution.
- Reactive transport processes:
  - Retardation (sorption)
  - Precipitation/dissolution
  - Degradation.

For more details on these transport processes the reader is referred to Section 9.

The conservative transport of a CoC is a function of the groundwater flow field (hydraulic gradients) and the physical transport properties of the aquifer (i.e. effective porosity and dispersivity, see Section 9). At project sites with an existing contaminant plume (e.g. brownfield sites) these transport parameters may be estimated from an analysis of the historic plume migration (often requiring numerical modelling to reconstruct the historic plume). At most proposed natural resource project sites, these transport parameters need to be estimated from the literature and/or similar analogue sites.

The conceptual model documentation should describe the site-specific data available for the transport parameters (effective porosity and dispersivity) and provide estimates of these conservative transport parameters for different hydrostratigraphic units. It is recommended that a range of values be provided for these transport parameters that reflect the uncertainty in these estimates. If no site-specific information is available on transport parameters, an attempt should be made to use field data from other sites with similar geological material. Literature values should only be used as a last resort. In any case, the selection of transport parameters should be clearly documented and justified.

The conceptual model documentation should also discuss the influence of aquifer heterogeneity and anisotropy (in particular in bedrock) on conservative transport, in particular the potential for transport along preferred flow paths such as high-permeability channels in heterogeneous porous media and faults in fractured bedrock (see Section 9 for more details).

The conceptual model documentation should discuss the potential for dilution of a CoC by mixing of impacted groundwater with clean groundwater and/or surface water (prior to reaching an identified VEC). Caution is required when invoking dilution in a groundwater system. Dilution assumes complete mixing along the groundwater flow path which requires significant distances (up to kilometers) and may never occur in heterogeneous systems. For example, recharge from precipitation may provide a significant volume (and potential dilution) to a contaminant plume in an aquifer. This recharge water may preferentially reside near the water table and provide little dilution to the contaminant plume which is migrating at greater depth in the aquifer. The use of dilution (and the implicit assumption of complete mixing) has to be evaluated and justified, if adopted in a conceptual transport model.

Most CoCs do not behave conservatively in the groundwater system. For those “non-conservative” CoCs, the reactive transport processes should be evaluated. The conceptual model should describe the relevant reactive transport processes such as sorption, precipitation/dissolution, and/or degradation. Figure 4-4 provides an example of a project in which geochemical controls represent a key aspect of the conceptual model.

Reactive transport processes are solute-specific and most are site-specific (taking into consideration local aquifer properties such as redox conditions, organic content etc.). Therefore consideration of reactive transport processes requires a data review of solute-specific information and often collection of site-specific data (e.g. site-specific field monitoring of water quality and/or laboratory testing using local soils and groundwater). The conceptual model should describe and evaluate the available evidence to support consideration of reactive transport processes.

In environmental assessments of natural resource projects, reactive transport processes such as sorption and/or precipitation/dissolution are often deliberately ignored because of the uncertainty of the reactive transport parameters (e.g. K_d) at the field scale. This approach typically produces more conservative results (i.e. more protective of the environment) and is therefore often preferred by the regulators.

However, neglecting reactive transport parameters in the formulation of a conceptual model does not always lead to conservative transport predictions. For example, consider the presence of a residual contaminant plume (say a metal) which should be remediated by pump and treat. If the metal is known to sorb to the aquifer material ($K_d >> 0$) a significant mass of the metal will be adsorbed to the aquifer material. Assuming conservative transport could therefore result in significant underestimation of the time (and pump volumes) required to clean up the residual plume.

For the above reason, reactive transport processes should always be considered during development of a conceptual model. For each CoC, the known reactive transport processes should be reviewed to determine whether they may apply at the project site and whether they need to be included in the numerical model. If reactive transport processes (for a known reactive CoC) are not included in the numerical model, this decision should be justified.

4.4.5 Sinks of CoCs

The conceptual model should include reasonable representations of the physical processes that may remove the CoC from the groundwater system, including:

- Seeps and springs discharging to ground surface
- Groundwater discharge into surface waters (lakes, streams)
- Groundwater abstraction (pumping)
- Inflow to open pit and/or mine workings
- Evapotranspiration (ET)
- Wetlands.

These physical "sinks" usually represent a subset of the groundwater discharges that may be included in the conceptual flow model. The conceptual model should account for where in the study area impacted groundwater is, or is expected to discharge to surface water, and/or be removed from the groundwater system via pumping (or other passive collection system).

For sites with existing contaminant plumes, available monitoring data should be reviewed and analyzed to determine the CoC concentration in groundwater discharging to surface or collected by wells/drains etc. In addition, the flow rates for these groundwater discharges should be reviewed to determine the contaminant load (equal to the concentration multiplied by the flow) for each CoC removed from the aquifer system.

For proposed project sites, CoC concentrations and contaminant loads discharging to the surface or planned to be collected should be estimated (to the extent practical). The conceptual model documentation should discuss uncertainties in these estimates and any potential changes over time.

4.5 METHODS OF CONCEPTUAL MODEL DEVELOPMENT

The development of a conceptual model requires a review and synthesis of a great deal of information and data, which is often spatially distributed and/or stored in large databases.

The following methods should be considered for model formulation:

- List potential data needs and associated potential data sources.
- Compile a database, preferably one that can be linked and viewed within GIS (e.g. ACCESS).

- Visualize temporal data in time trend plots (e.g. water levels, water quality).
- Visualize spatial data in maps and cross-sections (e.g. topography, geology, boreholes, water table maps, location of source areas, VECs, etc.) using suitable software (GIS, ACAD).
- Use high-resolution air photography or satellite imagery and internet-based mapping services (e.g. Google Maps).
- Supporting analytical calculations (Darcy calculations, travel times, mixing calculations etc.) to provide initial estimates of flow and CoC loads.
- Review of literature (e.g. estimation of flow and transport parameters not available from site-specific field work).

To the extent possible, an integrated software platform should be used for data management (including QA/QC) and spatial visualization (e.g. using GIS) to maximize the use of available data and to minimize errors in data transfer.

Examination of high-resolution air photos (or internet based mapping services where local air photos are not available) during conceptual model development is recommended. These air photos should be geo-referenced to allow at least some level of remote “ground truthing” of spatial data (e.g. locations of critical monitoring wells, zones of groundwater discharge etc.).

4.6 POTENTIAL ERRORS IN CONCEPTUAL MODELLING

The development of a conceptual model is one of the most important steps in groundwater modelling. At this stage of the modelling process, the modeller will have to make decisions on what processes to include (or exclude) and what simplifying assumptions should be made to achieve the modelling objective(s). Those decisions will strongly influence the mathematical model and ultimately the modelling outcome. It follows that errors in the conceptual model can propagate through the remainder of the modelling study, and if not detected early on, can potentially lead to invalid modelling results and conclusions. For this reason, a conceptual model should always be checked carefully for potential errors.

4.6.1 Inadequate Field Data

In some cases the available field data are either missing or inadequate to allow the development of a credible conceptual model. Inadequate field data is a common problem in natural resource projects, in particular for large projects (large foot-print) and/or projects in remote locations where field work is costly, and/or site access is difficult. Another problem in natural resource projects (in particular at the design stage) is that the field data were oftentimes collected for another purpose (say geotechnical study) and may not be adequate for the purpose of groundwater modelling.

If critical data gaps are identified, these gaps need to be filled by additional field work before the conceptual model can be completed and the modelling study can proceed. In some cases such additional field work can be avoided (or at least postponed) by: (i) using two alternative conceptual models that cover the uncertainty due to the data gap; and/or (ii) using conservative assumptions in the conceptual model.

For example, the presence of a fault may have been identified at a project site (from drilling and/or structural analysis) but no hydraulic testing is available to determine whether this fault should be considered a high-K conduit (and a potential preferential flow path for a contaminant) or a barrier to groundwater flow and contaminant transport. This data deficiency should be identified as a critical data gap during conceptual model development.

The preferred course of action is to complete additional drilling and/or hydraulic testing to determine the hydraulic properties of this structure. If that is not feasible, two alternative conceptual models could be developed (one assuming the structure is highly permeable and another assuming it is a low-permeability barrier). Both conceptual models would have to be implemented into a mathematical model and calibrated. If both scenarios are plausible, the more conservative scenario should be assumed for model predictions related to environmental impact assessment.

4.6.2 Conceptual Model is Inconsistent with Existing Data

Conceptual models may be inconsistent with existing data. This error is quite common because the conceptual model is preliminary and qualitative, in particular during the initial modelling stages when the conceptual model has not yet been rigorously tested against field observations. Inconsistencies between the conceptual model and field observations are often recognized during model calibration because incorrect conceptual models can result in significant difficulties in calibrating a model to the field data.

Typical errors in the conceptual model that could result in consistent biases between simulated and observed heads (or concentration) include:

- Incorrect selection (spatial distribution) of hydrostratigraphic units (e.g. presence of a high-permeability channel).
- Incorrect boundary condition (e.g. use of a constant head boundary for a small lake that is not hydraulically connected to the groundwater).
- Omission of a key source or sink of groundwater (e.g. a drain system in a tailings dam not documented).
- Omission of a key transport process (e.g. irreversible sorption of a contaminant).
- Incorrect historic source term (e.g. timing and magnitude of historic seepage from a tailings dam).

The modeller should carefully examine the calibration results for consistent bias in residual errors (in space and time) and/or consistent “outliers” which could be indicative of problems with the conceptual model (see Section 7.3 for more details). The modeller should continually challenge his/her conceptual model and be “open-minded” to attempt changes in aspects of the conceptual model during model calibration that carry significant uncertainty.

4.6.3 Conceptual Model Misses a Key Process

The development of a conceptual model requires the modeller to identify the key processes that need to be included in the numerical model. By virtue of this selection there is a risk that a key process has been overlooked and is not included in the model. Examples of key processes that may not be apparent from the monitoring data and therefore may be overlooked during conceptual model development include:

- Preferential flow and/or transport in heterogeneous aquifers (debris flow sediments; glacio-fluvial sediments, fractured bedrock).
- Preferentially oriented flow and/or transport in anisotropic aquifers (fractured bedrock).
- Complex reactive transport processes (e.g. non-linear sorption, redox sensitive transport).
- Change in reactive transport conditions over time (e.g. change in redox conditions, depletion of sorption sites etc.)

To avoid this problem, the modeller should review possible flow and transport processes that may be active at the project site. For those processes that are uncertain, preliminary sensitivity analyses (using analytical solutions or a simple numerical model) can be carried out to determine whether these processes can be neglected for the purpose of the study or whether they should be included. If the project outcome is sensitive to those assumptions, additional data should be collected and the conceptual model should be refined. If additional data collection is not feasible (or does not resolve the uncertainty) conservative assumptions should be adopted.

4.6.4 Simplifying Assumptions are Non-Conservative

Conceptual models require the use of simplifying assumptions to reduce real-life complexity to a manageable level that can be incorporated into a model. The precautionary principle should be applied when making simplifying assumptions for environmental assessments, i.e. simplifying assumptions should always be conservative in the sense that they result in more, rather than less, predicted impact. A classic example is the assumption of conservative transport for contaminants which are known to be reactive (e.g. metals) which would tend to result in the prediction of greater water quality impacts.

The effect of simplifying assumptions on model predictions is not always straightforward and the modeller (or reviewer) should always confirm that a given simplifying assumption in fact results in more conservative predictions, in particular in the context of environmental impact assessments.

In Section 4.4.3 we described an example where the assumption of conservative transport did not result in a conservative transport predictions (i.e. residual contaminant mass sorbed to aquifer material was ignored). A similar error is sometimes made when conceptualizing the flushing of a contaminant plume from a source term, for example pore water in a tailings impoundment. In this case, the assumption of conservative transport would result in much faster flushing of the contaminant from the tailings pore space than might occur in reality, perhaps due to continued dissolution of a contaminant precipitated out during tailings deposition. If the geochemical conditions in the tailings are not well-understood, a more conservative approach would be to assume a constant concentration in the tailings pore water.

Another example of a simplifying assumption that is commonly misinterpreted is the assumption of a homogeneous aquifer. The assumption of a homogeneous aquifer greatly simplifies the modelling and may be adequate for predicting groundwater flow. However, this assumption may not be conservative when predicting the breakthrough of a contaminant plume. Some may argue that aquifer heterogeneity spreads the contaminant plume and hence dilutes the plume, thus suggesting that the assumption of a homogeneous aquifer is conservative. The opposite is in fact true when predicting contaminant breakthrough at a discrete location. Heterogeneity can result in strongly preferential flow path (in particular in fractured bedrock) with very limited dilution and dispersion over great distances (up to kilometers).

4.6.5 Conceptual Model is Not Updated

A conceptual model is always a “work-in-progress” and may require significant updating during the model study. Tight timelines and/or budget constraints often force the modeller to continue using a model that is based on an incorrect conceptual model (e.g. as evidenced by poor model calibration and/or new field data).

There is also a natural tendency to resist the complete rethinking of a conceptual model and “stick to” an existing model simply because the modeller invested a lot of time and effort into building this model. This tendency does not necessarily imply bad intent on part of the modeller but instead is a natural tendency of people that have invested significant effort. This problem is more commonly observed with very complex models (which typically cost a lot more time and money to construct). This issue is one of the main disadvantages of using very complex models.

One of the best ways to ensure that the modelling process “stays honest” and to ensure that the conceptual model is updated when required, is to provide for model review throughout the modelling process (see Section 2 and 11). Even an informal, internal peer review provides additional dialogue and may uncover problems with the conceptual model that were hitherto not recognized by the modeller.

4.6.6 Conceptual Model Does Not Consider Future Processes

Most model studies are motivated by the need to predict a future behavior that cannot be readily observed today. The lack of knowledge about future processes can sometimes lead to an incomplete, or even missing, conceptual model of those processes. For example, a future change in land use may result in significant changes to local recharge to groundwater and hence the aquifer behavior. Another example that has received much attention recently is the potential for climate change which may affect recharge to groundwater system.

The extent to which future processes should be considered in the conceptual model depends on the project and in particular the time-frame of modelling. Natural resource projects (whether mining or large groundwater extraction projects) tend to have a time frame of decades and associated contaminant transport problems may require models that simulate transport for up to a century or longer.

For those extended time periods, an effort should be made to address potential future changes to the aquifer system (whether induced by the project or otherwise) in the conceptual model, at least qualitatively. In some cases, selected sensitivity runs for potential future “upset” conditions may be required (using an analytical or numerical model) to determine their potential influence on long-term predictions.

4.7 CASE STUDY EXAMPLE

4.7.1 Case Study 2 – Underground Mine

The conceptual model for the underground mine project includes delineation of hydrostratigraphy, hydrogeologic properties of those strata, relationships between groundwater and surface water features, regional hydrologic (climatic) conditions, the mine development and closure plan, and an understanding of potential receiving environments. Figure 4-7 presents a cross-sectional illustration of the key component of the groundwater system. The reader is referred to Appendix C for additional details regarding this Case Study.

Based on the complexity of the site and level of risk associated with valued ecosystem components, a 3D MODFLOW model was developed. The model was conceptualized using drilling records and geologic data from a number of sources, including:

- Geologic mapping/model,
- Exploration drilling and testing, and
- Residential well logs from MOE’s WELLS database

Although continuum models, like MODFLOW, do not address discrete bedrock fractures, the modeller notes that the applicability of an equivalent porous media (EPM) approach to simulations of flow and transport in heterogeneous, fractured bedrock settings has been well proven and documented in other studies elsewhere. However, the justification did not appear to be based on assessments of the conditions of the bedrock units at the site. The assumption of equivalent porous medium became a significant point of uncertainty from the perspective of the government reviewers. Prior field investigations were acknowledged and data was incorporated into the conceptualization and calibration procedures. This data was, however, limited spatially and temporally.

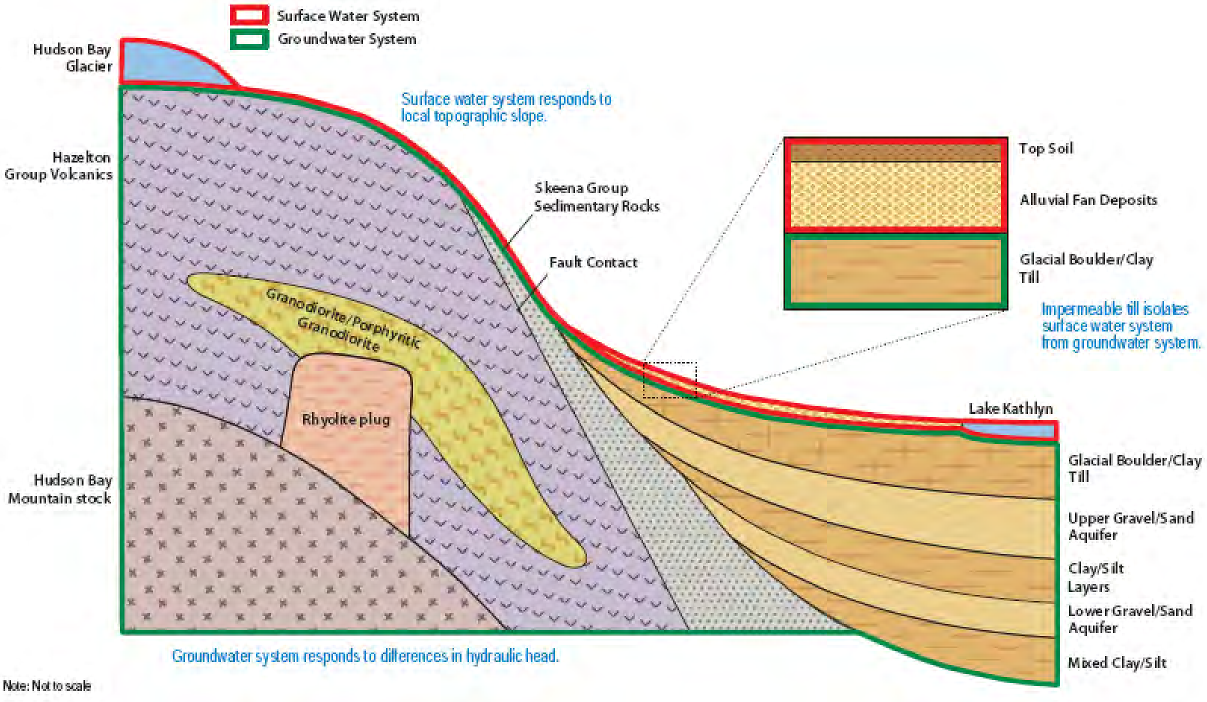


Figure 4-7: Conceptual model used for MODFLOW modelling

The conceptualization of the hydrostratigraphy and groundwater flow is generally well presented in this Case Study. However, the results are prefaced by the extremely limited dataset on which model conceptualization and calibration were based. Furthermore, major assumptions of equivalent porous medium for fractured bedrock, horizontal isotropy of hydraulic conductivity of the various fractured bedrock units and effective porosities did not appear to be justified by data or assessments from the site. These issues introduced significant uncertainties to assessing how the proposed mine will affect changes in groundwater flow and contaminant travel times, and impacts of these changes to local high VEC water users' streams.

As recommended in these guidelines (see Figure 2-2), consultation with government technical staff during the development of the modelling objectives, the conceptual model, and the data collection requirements could have helped to identify these issues and questions much earlier in the modelling process.

SUMMARY POINTS FOR CONCEPTUAL MODEL DEVELOPMENT

1. A conceptual model is a simplified representation of the essential features of the physical hydrogeological system and its hydraulic behavior. The development of a conceptual model is one of the most important aspects of a groundwater modelling study.
2. The conceptual model should be developed using the principle of simplicity and should be continually updated as the understanding of the system is improved, or as questions and modelling objectives evolve.
3. The conceptual model should be described in words and supported by diagrams, figures, graphs, and tables. For example, the conceptual model documentation should provide a qualitative and pictorial description of the groundwater flow regime. Simplifications and assumptions should be documented and supporting information provided to justify that assumptions are reasonable.
4. Conceptual model formulation should include consideration of (and the report should describe) the presence and spatial distribution of major hydrostratigraphic units and their hydraulic properties.
5. Model conceptualization should include a description and quantification of recharge and discharge processes, including seasonal variations.
6. The conceptual model documentation should discuss the main aspects of groundwater-surface water interaction, with special emphasis on streams and/or lakes which have been identified as high VECs.
7. During model conceptualization, a groundwater budget should be prepared. The water budget should quantify all major inflows to and outflows from the conceptual model domain.
8. A conceptual model of contaminant transport should be consistent with the conceptual model of groundwater flow. The determination of appropriate source terms is a critical step in formulating a conceptual transport model. The conceptual model documentation should describe the applicable transport processes for the contaminant(s) of concern.

5 MATHEMATICAL MODEL SELECTION

5.1 OVERVIEW

Once a conceptual model has been developed (Section 4) the groundwater modeller has to select an appropriate mathematical model to represent the conceptual model. This process encompasses (i) the selection of analytical versus numerical models; (ii) the selection of spatial and temporal dimensionality for numerical models; and (iii) selection of a computer code or analytical solution approach.

The selection of a mathematical model involves consideration of the following (see Figure 5-1):

- Modelling objectives
- Conceptual model
- Modelling complexity
- Modelling tools available
- Modelling constraints.

The most important factors to consider in mathematical model selection are modelling objectives and the conceptual model. The modelling objectives and site conceptual model are important because they determine what processes should be simulated and what level of accuracy is required. The required accuracy determines the model complexity which in turn influences the selection of the mathematical model, and the extent of data collection used to drive the model (Figure 5-1). For example, an analytical solution may be adequate for order-of–magnitude estimate of steady-state inflow to an open pit. In contrast, a three-dimensional numerical model may be required if the modelling objective calls for an estimate of pit inflow to an accuracy of +/- 25%.

The conceptual model provides a framework for selecting the appropriate level of modelling complexity and ultimately mathematical model selection by defining the relevant processes that must be included (Figure 5-1).

Note that the process of mathematical model selection is closely related to the development of a conceptual model (Section 4) but usually requires a greater level simplification due to mathematical constraints. These guidelines therefore distinguish mathematical model selection from the more qualitative model conceptualization.

This section introduces the key definitions and concepts and provides guidance on appropriate model selection for natural resource projects. This section includes a discussion of the types of models commonly used, their capabilities and limitations, and their applicability to various physical conditions and applications.

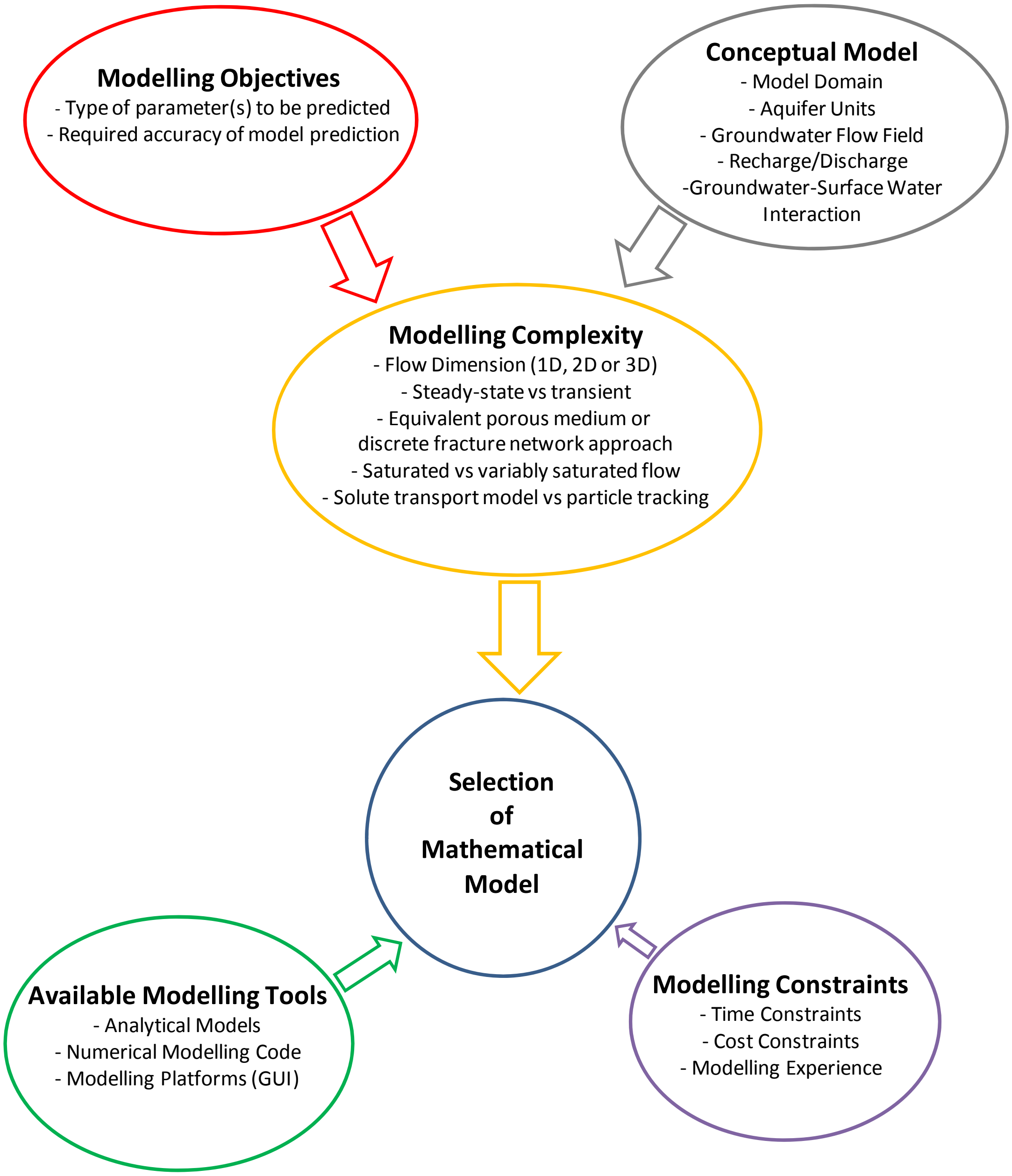


Figure 5-1: Factors influencing selection of a mathematical model.

5.2 SCOPE OF MATHEMATICAL MODEL

The first step in model selection is the definition of an appropriate scope of modelling. This scoping step will drive the decisions regarding analytical versus numerical modelling, dimensionality of the model, and selection of an appropriate code or solution to address the modelling objectives. The following questions have to be evaluated during model scoping:

- Should the groundwater flow problem be simulated in three dimensions or can it be simplified to a 2-dimensional problem, an axi-symmetric (radial) problem or even a one-dimensional problem? Can analytical approaches be used (i.e.1D or uniform radial flow)? Is vertical flow important to model?
- Are conditions over time important to model? Should the groundwater flow problem be simulated using a transient model or can it be approximated by a steady-state model? If so, what steady-state conditions should be modeled (e.g. high flow, low flow or average flow, or a representative range)?
- If the setting is bedrock, would an equivalent porous medium approach be appropriate and can this approach be justified, based on site characteristics? If not, would other approaches like discrete fracture network or dual porosity model be required and what data from the site is needed to support these models?
- Can flow in the unsaturated zone (or in perched zones) be ignored or is a variably saturated flow model required?
- Should contaminant transport be simulated using a contaminant transport model or is the use of particle tracking adequate?
- Should geochemical aspects of contaminant transport be simulated or is the use of a conservative solute transport model adequate?

The above questions have a strong influence on the degree of complexity of the mathematical model and often the type of model (i.e. code) required for the modelling study.

The answer to these questions depends on the modelling objectives and the required model accuracy. The selected scope of modelling depends on the conceptual model and the available field data on which the conceptual model is based.

The following sections provide guidance on the appropriate scope of groundwater modelling to assess impacts on natural resource projects.

5.2.1 Model Dimension

Spatially, groundwater flow systems are three–dimensional; that is, they can have a significant flow component along each of the three orthogonal axes, x, y, and z.

Using the principle of parsimony or simplicity (see Section 4) the modeller should seek to simplify the flow problem as much as possible. This includes an assessment of whether the flow problem can be reduced to a 2D or even 1D problem (if flow component is not significant in 1 or 2 of the other dimensions). The following sections discuss the criteria that should be considered in determining the appropriate dimension(s) to be used in the groundwater flow (and transport) model.

5.2.1.1 Groundwater Flow Field and Hydraulic Gradients

The modeller (or reviewer) should inspect the groundwater flow field to determine whether groundwater flow is predominantly in one, two, or three directions. Groundwater flow in many larger (regional) aquifer systems is predominantly horizontal with only a small vertical flow component. The relative contributions of horizontal versus vertical flow can be estimated using simple Darcy calculations (assuming appropriate estimates of horizontal/vertical hydraulic conductivity and hydraulic gradients). If the vertical flow component is small (say less than 5%) a two-dimensional representation of the regional groundwater flow field (using a plan view model) may be adequate.

Very few natural groundwater flow systems are one-dimensional due to the influence of local boundaries (e.g. valley boundaries, bedrock topography). Hence, a one-dimensional flow model is rarely appropriate, in particular for smaller aquifers which are strongly influenced by local boundaries. A one-dimensional approximation of groundwater flow may be adequate to simulate groundwater flow in a certain portion of a more complicated flow field. For example, groundwater flow from a relatively uniform hill side to a larger valley aquifer may be represented using a one-dimensional flow model.

In practice, the scale of groundwater resource projects and their influence on the groundwater flow field (see below) rarely justify the use of a one-dimensional flow model. One-dimensional models are predominantly used for initial scoping calculations (e.g. for conceptual modelling) typically in combination of simple analytical solutions such as a one-dimensional version of Darcy’s Law (see below).

5.2.1.2 Degree of Heterogeneity

The modeller (or reviewer) should consider the degree of heterogeneity in the aquifer system when selecting the appropriate dimension of the mathematical model (see Section 4).

For example, the presence of a confining till layer separating a shallow aquifer potentially influenced by seepage from a mine waste unit from a deeper drinking water aquifer likely requires a discrete representation of this unit. In this scenario the potential movement of fluids between the surficial and deeper aquifers is a primary issue of concern. In order to model vertical flows, this scenario requires at least a two-dimensional cross-sectional model if flow in the transverse direction is small, or a full three-dimensional model.

Alternatively, highly permeable units which could represent preferential flow channels (e.g. a paleochannel or a fracture zone) may require explicit representation (in particular if contaminant transport is of concern) requiring a 2D or even a 3D modelling approach.

5.2.1.3 Type of Hydraulic Stresses and Influence on Flow Field

The modeller (or reviewer) should consider the type of stresses in the aquifer system when selecting the appropriate dimension of the mathematical model.

The most common stresses simulated in the natural resource industry include pumping, pit dewatering, underground dewatering and mine waste seepage (from TSF, WRDs and/or backfilled pit/underground workings.

Pumping from an extraction well creates a radial flow field which is best represented by a 3D axi-symmetric model or a 2D plan view model. A three-dimensional representation of a pumped aquifer may be required only if the pumping well penetrates a small portion of the aquifer (“partially penetrating” well) and/or the aquifer has significant vertical heterogeneity (e.g. confining layers).

Excavation of an open pit and associated dewatering tend to create a significant drawdown in the surrounding aquifer(s) somewhat analogous to a pumping well. In most mining projects, open pits reach significant depths and a representation of the vertical flow field is important. If the pit geometry is regular and the surrounding groundwater flow field is relatively uniform, a cross-sectional model may be adequate to simulate flow to the pit. In a more complex setting, a fully three-dimensional representation of the open pit and the surrounding aquifer may be required.

Figure 5-2 shows an example of a proposed open pit located in a complex setting where a three-dimensional flow model is appropriate. First, the open pit reaches a significant depth (300m) and intercepts bedrock units with greatly varying hydraulic conductivities. Second, the groundwater flow field is not uniform due to the presence of a lake on one side of the open pit and a steep mountain on the other side of the open pit. Finally, the open pit is intersected by several faults which are inferred to have a higher hydraulic conductivity than the local bedrock. The complexity of this setting prevents the use of a simplified cross-sectional model to simulate pit dewatering.

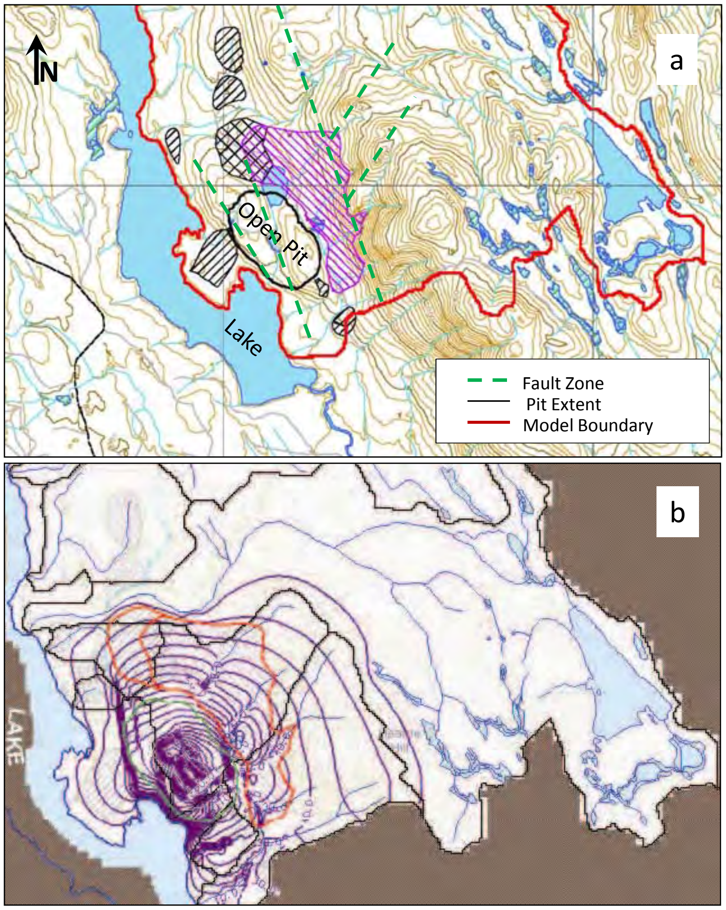


Figure 5-2: Example of a three-dimensional pit inflow problem. The upper panel shows a 2D plan view of the site, illustrating the proximity of the open pit to a nearby lake to the west and high relief to the east. The open pit is about 300m deep and intersects bed

Mine waste units (such as TSFs or WRDs) tend to have a significant foot-print area and therefore commonly have a large effect on the groundwater flow field. As a result, the simulation of seepage from these mine waste units requires at least a 2D plan view model and often a three-dimensional model. The large size and regular shape of many mine waste units may result in a relatively uniform flow field (in x-y) which may be simulated using a cross-sectional model (see Appendix C1 for example Case Study 1).

5.2.1.4 Type of Remedial Work and Influence on Flow Field

The modeller (or reviewer) should consider the type of remedial work and its influence on the groundwater flow field in selecting the appropriate dimension of the mathematical model.

For example, an assessment of the efficacy of a shallow seepage collection drain and/or a partially penetrating cutoff wall requires at least a cross-sectional model or even a fully three-dimensional model. In contrast, an assessment of a fully penetrating drain and/or cutoff wall could be simulated in a two-dimensional (plan view model).

5.2.1.5 Required Model Accuracy & Data Uncertainty

The required model accuracy and data uncertainty influences the selection of an appropriate dimension for the flow and/or transport problem. In many applications the required model accuracy is not high enough to justify the use of a fully three-dimensional model. High model accuracy is often not warranted because of the lack of field data.

For example, if hydraulic conductivity estimates for the main aquifer influencing pit inflow have an uncertainty of two orders of magnitude, a 10% or 20% error introduced by ignoring the radial component of groundwater flow to an open pit may be acceptable. Often, analytical solutions can be used to estimate the error introduced by reducing the dimensionality of the flow problem.

Any simplification of a three-dimensional flow problem to a 2D (or even 1D) problem should be justified. An estimation of the resulting error should be provided and the potential implications for model predictions should be discussed.

5.2.1.6 Scale Issues

Most groundwater models recently developed to assess environmental impacts for larger mining projects used a basin-wide approach, i.e. a single three-dimensional model that encompasses the local watershed(s) is used to assess various aspects of the proposed project (see Table 1-1 in section 1).

These basin-wide groundwater models have the advantage that the domain boundaries are typically well-defined and that all three flow components are included. These 3D models are often not well-suited to evaluate specific aspects of groundwater flow due to the large scale of the model; however a coarse-grid regional model may be used to define boundary conditions for a fine-grid local site model.

As another example, the design of a passive pit dewatering system (with drain holes at various pit benches) may be better evaluated using a detailed cross-sectional model (using Cartesian or radial coordinates). This way, additional detail in the vertical (e.g. presence of pit benches, and confining layers) can be included in the 2D model that would unnecessarily “burden” the 3D basin model.

These guidelines recommend the use of a combination of modelling approaches from basin-wide models (in 3D) to detailed sub-models (ranging from 1D to 3D) to assess different aspects of the groundwater flow system.

Case Study 1 provides a good example of the use of multiple models for an assessment of environmental impacts for a proposed open pit mine (see Section 5.6.2).

5.2.2 Time Dependency

Almost all groundwater systems are inherently transient (dynamic) and the modeller has to determine whether this time dependency should be explicitly modeled or whether a steady-state (essentially does not change over time) simulation is adequate to satisfy the modelling objectives. Note that solute transport is, by definition, a transient process. Solute transport may be simulated assuming steady-state or transient flow conditions (see Section 9).

Many groundwater flow systems in British Columbia are highly transient, including:

- Aquifer(s) with strongly seasonal recharge (e.g. snowmelt dominated recharge in high elevation and/or cold region sites)
- Aquifer(s) influenced by variable pumping stresses (e.g. seasonal pumping, multiple users)
- Aquifer(s) influenced by seasonal irrigation (e.g. farmland)
- Coastal aquifer(s) or aquifers near large rivers which are tidally influenced (e.g. Fraser River).

The use of a transient groundwater flow model should be considered for any of these highly transient groundwater flow systems listed above.

A review of recent modelling studies carried out for EA submissions in British Columbia indicates that most flow models used for proposed mining projects assumed steady-state conditions (see Table 1-1 in section 1). Transient flow models were more commonly used in the assessment of groundwater resource projects which often require transient calibration of the model to pumping tests (Table 1-1).

The modeller has three options to represent a transient groundwater flow system:

- Simulate transient flow conditions (transient model)
- Simulate average flow conditions (steady-state model)
- Simulate high and low flow conditions (steady-state model).

Given the highly transient nature of most groundwater systems in B.C., and the complexity of a transient model, the first attempt to characterize the groundwater system should include a range of simulated conditions to bracket the existing variability, and the expected changes resulting from the proposed development.

It is good modelling practice to first develop and calibrate a steady-state model using average flow conditions for model calibration. If required, the transient aspects of the flow (or transport) problem can then be modeled using the calibrated steady-state model as initial conditions.

Fully transient models are an order of magnitude more difficult to develop and calibrate than steady-state models so careful consideration should be given to whether a transient model is required. Which modelling approach is selected depends on the flow system studied and the modelling objectives.

Consider the example of a flooded open pit which is located in an area with highly seasonal recharge (refer to Figure 4-3a/b in section 4). The flooded open pit is hydraulically connected to a bedrock aquifer which shows significant seasonal variations in groundwater levels (Figure 5-3). During the high-flow period, the groundwater is recharging the open pit and during the winter low-flow period, the open pit is recharging the aquifer. A steady-state model (using average recharge conditions) simulates the “average” water levels and the “average” (or net) flux to/from the open pit (Figure 5-3). However, a transient model (using the seasonal recharge distribution) would be required to assess the seasonal inflows and outflows to/from the open pit. In this example, the seasonal variations in (contaminated) groundwater discharge to the flooded open pit (and the nearby river) were important, and hence a transient model was required.

When simulating a transient problem assuming steady-state conditions, the modeller (or reviewer) should ensure that this approximation yields conservative model predictions. In the above example, high flow (steady-state) conditions could have been simulated to provide a conservative estimate of discharge of contaminated groundwater to the open pit and nearby rivers.

Any simplification of a transient flow problem to a steady-state problem should be justified. It should be demonstrated that this simplification yields conservative estimates of environmental impacts.

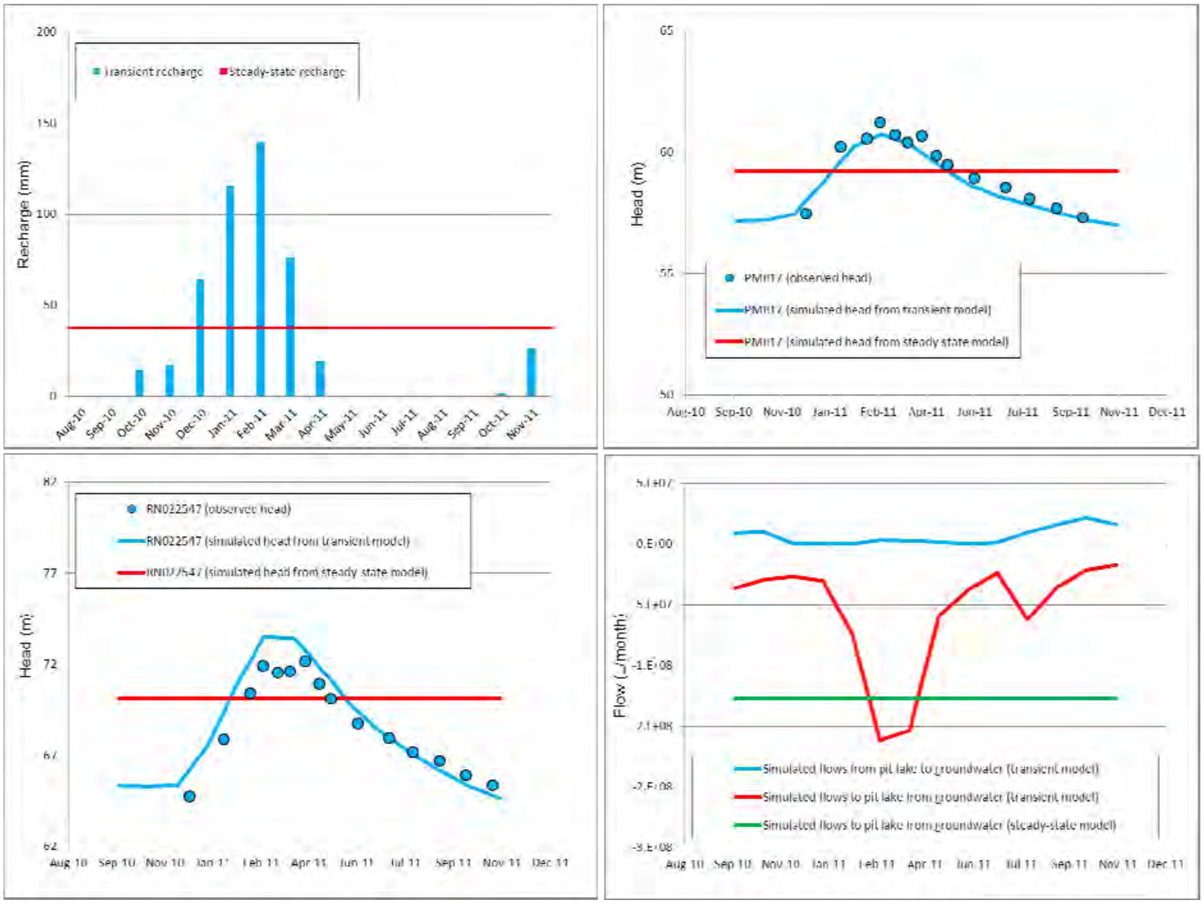


Figure 5-3: Comparison of steady-state and transient flow solutions for a highly transient groundwater flow system. Upper left panel shows estimated monthly recharge to the site and mean annual average. Lower left and upper right panels compares observed groundwater levels with simulated hydraulic heads (using transient and steady-state model). Lower right panel shows simulated groundwater flow from/to open pit using transient and steady-state model.

5.2.3 Type of Flow Domain

Three different approaches are available to simulate groundwater flow and solute transport in natural aquifer systems:

- Equivalent porous medium (“EPM”)
- Discrete fracture network (“DFN”)
- Dual porosity medium (“DPM”).

The EPM approach assumes that the aquifer system can be represented by an equivalent porous medium, i.e. that the aquifer system behaves like a porous medium and standard flow and transport equations apply. The EPM approach is commonly used for unconsolidated materials such as overburden soils (colluvium), fluvial, alluvial and glacio-fluvial sediments, and highly weathered bedrock with high primary porosity.

The EPM approach is also commonly used to describe groundwater flow through fractured bedrock in which the primary porosity is very low and the effective permeability is controlled by fractures, fissures and bedding planes (i.e. secondary permeability). This approach is based on the assumption that at a sufficiently large scale (i.e. the representative elementary volume or REV) the bedrock mass will behave like a porous medium and can be described by “effective” hydraulic properties (e.g. specific discharge or flow per unit cross-sectional area).

The majority of groundwater modelling codes (including the codes discussed in Section 5.4.2) use the EPM approach to model groundwater flow.

In the discrete fracture network approach, it is assumed that flow through the bedrock matrix is negligible and all groundwater flow occurs through an interconnected network of fractures. Such a discrete fracture network may either be described explicitly (with known geometry) or generated randomly using fracture network statistics (e.g. Dershowitz et al., 2004; Parker and Cherry, 2011). Sophisticated modelling codes are available to generate DFNs and to simulate groundwater flow and solute transport in such a medium, including FracMan (available from http://www.fracman.com/) and Fractran (available from http://www.waterloohydrogeologic.com/software/fractran/fractran_ov.htm).

Flow and transport in fractured bedrock and structured porous media (e.g. fractured sandstone) can be described using dual porosity models (DPM). This approach assumes that the medium consists of two regions, one associated with the macropore or fracture network and the other with a less permeable pore system of soil aggregates or rock matrix blocks (Gerke and van Genuchten, 1993). Different models exist to describe the nature of flow and transport in these two domains and the extent of their interaction. In its simplest form, groundwater flow and advective transport is assumed to only occur in the highly permeable (“active”) domain. Groundwater flow in the low-permeable (“inactive”) domain is assumed to be negligible but this stagnant zone influences solute transport by diffusion.

At present the DFN and dual porosity models are predominantly used in research and/or in assessment of contaminated sites with very high risk and/or consequence (e.g. storage of radionuclides, large contaminated sites impacting drinking water supplies, etc.). The primary challenge with the DFN and DPM models is model parameterization. A characterization of the fracture network and/or the dual porosity regime requires extensive field studies and/or detailed model calibration usually not available for natural resource projects.

These guidelines generally recommend the use of the EPM approach for groundwater modelling in support of natural resource projects in fractured bedrock settings but the application must be reasonably justified (e.g. supporting site data, simple objectives, etc.). Note, however, that the use of the EPM approach in moderately to sparsely fractured bedrock significantly increases model uncertainty. For example, an EPM model may correctly predict the overall inflow to an open pit but may not be able to predict the exact location where such an inflow will occur. Even greater uncertainty should be expected when modelling transport processes with an EPM approach, as the direction and timing of contaminant transport can be strongly influenced by flow through discrete fractures (see also section 9). If applied to fractured bedrock, the limitations of the EPM approach and potential implications for model predictions should be discussed in the model report.

DFN or DPM approaches should be considered in projects where the modelling objectives justify these approaches (e.g. contaminant transport in fractured bedrock with high risk/consequence) and the supporting site characterization data is available.

5.2.4 Variably Saturated Flow

Most traditional groundwater models simulate “saturated flow”, i.e. water movement in the saturated zone below the water table. In this approach, water movement in the “vadose zone”, i.e. the unsaturated zone above the water table, is ignored. For example, most groundwater models apply recharge directly to the top of the aquifer without simulating the processes of infiltration through the vadose zone, transpiration from the root zone, etc.

During model scoping, the modeller (or reviewer) should determine whether water movement in the vadose zone should be explicitly simulated. Water movement in the vadose zone is described by the Richards equation (Richards, 1931) and requires knowledge about the unsaturated hydraulic conductivity which is a function of the degree of saturation of the medium.

In the context of natural resource projects, an in-depth assessment of water movement in the vadose zone may be required for the following conditions:

- Assessment of seepage from a mine waste facility (e.g. a tailings impoundment)
- Simulation of groundwater flow with significant influence of perched zones
- In-depth assessment of soil cover performance.

Several “variably saturated” flow models have been developed which simulate the continuum from unsaturated flow in the vadose zone to saturated flow in the saturated aquifer (Section 5.4.2). Solution to the Richards equation is non-linear and requires significantly greater computing effort than conventional saturated flow models. This approach requires significantly greater vertical discretization to achieve model convergence.

For the reasons listed above, variably-saturated flow (and transport) models are commonly simplified to 2D or even 1D flow problems to reduce model complexity and computing time.

The use of variably saturated flow for large-scale models of groundwater flow (e.g. at the basin scale) is uncommon and not recommended. In most cases inadequate field data are available to either parameterize and/or calibrate the model. This tends to result in over-parameterization which makes the model less transparent and unnecessarily complex.

In some instances, a variably-saturated flow solution may be used to avoid numerical problems associated with simulation of the water table (“phreatic surface”) in regional aquifers (Section 5.4.2). Some modelling codes provide options for simplified formulations of the hydraulic conductivity function to use this approach at the regional scale (e.g. FEFLOW; MODFLOW-SURFACT). If this approach is used, the model parameters often do not represent realistic physical parameters (because the simplified formulations are not physically based).

If a variably-saturated flow solution is used to solve a 3D flow problem, this approach and the hydraulic parameters assumed for the unsaturated zone, should be justified and documented.

5.2.5 Solute Transport Model versus Particle Tracking

If the modelling objectives for a given project include an assessment of contaminant transport, then the modeller (or reviewer) should determine whether solute transport can be simulated using particle tracking or whether a full solute transport model is required.

Particle tracking visualizes the flow path of a solute and allows an estimation of travel times assuming advective transport. This method does not allow the prediction of contaminant plume migration in space and time (see Section 9 for more details).

Solute transport models simulate the movement of contaminant plumes assuming all dominant transport processes (i.e. advection, dispersion, and diffusion). These models allow a quantitative assessment of contaminant transport, including the prediction of the spatial distribution of contaminant concentrations in the aquifer and/or contaminant breakthrough at a given location (see Section 9 for more details).

Particle tracking provides significant insight into the groundwater flow field and the resulting flow paths and should always be used, at least as a screening tool, for contaminant transport problems.

Solute transport modelling should be considered for an impact assessment of natural resource projects if potential CoCs have been identified in the project AND any of the following conditions apply:

- Particle tracking suggests that CoCs may reach VEC(s) (e.g. streams) via groundwater, and
- Conservative mixing calculations (i.e. mixing of contaminant load into receiving water without chemical reactions based on particle tracking and/or load balance modeling) suggest that contaminant concentrations may exceed applicable guidelines
- Significant changes in the source concentration of a CoC are expected over the course of the project
- Significant dispersion of the contaminant plume is anticipated and poses a risk to the environment
- Significant dilution of the contaminant of concern is expected along the flow path due to dispersion and/or dilution (e.g. by recharge or groundwater inflow); or
- The CoCs are known to be reactive and geochemical reactions may significantly influence contaminant transport (see section 5.2.6 below)

These guidelines recommend the use of a phased approach for assessing contaminant transport and associated water quality impacts for natural resource projects. Initially, particle tracking should be used to determine the potential flow paths and the risk to VECs. Preliminary (conservative) estimates of contaminant loads and/or contaminant concentrations to VECs (e.g. rivers, lakes) should be obtained to assess whether applicable guidelines may be exceeded. If these conservative calculations indicate a potential risk to VECs, then solute transport modelling should be considered.

Note that solute transport modeling may not be required if the project descriptions includes mitigation options (e.g. lining of a tailings facility, placement of waste rock under water) that eliminates or at least adequately reduces the contaminant source(s).

5.2.6 Conservative versus Reactive Transport

Solute transport in the subsurface is commonly influenced by chemical reactions occurring: (i) among different solutes (dissolved in groundwater); and/or (ii) with the surrounding solid phase (i.e. the soil particles or rock surface).

Common reactive transport processes encountered in aquifers include: (i) sorption/desorption; (ii) precipitation/dissolution; and (iii) redox reactions (see Section 9 for more detail). Another category of reactive processes is biologically facilitated transformations, like dentrification. Although reactive transport processes have been documented and studied for many years, their influence can vary greatly from site to site. As a result, site-specific information is usually required to quantify their effects on contaminant transport.

In most cases, reactive transport processes tend to reduce contaminant concentrations. Hence, consideration of reactive transport processes tends to yield non-conservative water quality predictions as there are sinks for the solute. For this reason, the use of reactive transport models should be limited to situations where all of the following situations apply:

- Conservative transport modelling has demonstrated that there is a potential exceedance of applicable standards in one or several CoCs.
- Reactive transport processes included in the model are well-established in the literature.
- Reactive transport parameters used in the model are
    - based on site-specific laboratory/field testing and/or
    - calibrated against field observations (e.g. breakthrough or plume distribution.)

The above guidelines are consistent with the phased approach for contaminant transport described recommended in Section 5.2.5. Conservative transport modelling should precede reactive transport modelling to identify whether the additional complexity of reactive transport modelling is justified. This phased approach ensures that the influence of the reactive transport assumptions on water quality predictions is transparent.

If a reactive transport model is selected, the modeller should justify this decision, and provide details on model parameterization and calibration, including supporting lab/field studies.

Note again that solute transport modeling (whether conservative or reactive) may not be required provided the project description includes mitigation options (e.g. lining of a tailings facility, placement of waste rock under water) that would eliminate (or adequately reduce) the risk to any VECs (and this can be demonstrated using conservative mass balance calculations and/or particle tracking.

5.3 OVERVIEW OF MODELLING TOOLS

The groundwater modeller has a wide variety of modelling tools available at his/her disposal to model the groundwater system. The modelling tools can be broadly grouped into three categories:

- Analytical Models
- Numerical Models

- Analytic Element Models.

This section provides an overview of these modelling methods and describes their main advantages and disadvantages.

5.3.1 Analytical Models

5.3.1.1 Definition

Analytical models use exact solutions to the equations that describe groundwater flow or contaminant transport. In order to produce these exact solutions, the flow/transport equations have to be considerably simplified such that they are typically applicable only to simple flow and contaminant transport systems. Analytical models can be simple formulae, spreadsheets, or sequences of calculations packaged in a piece of software.

5.3.1.2 Model Use

Table 5-1 lists the advantages and disadvantages of analytical model vis-à-vis numerical models. The main advantage of analytical models is the ease of use and transparency of such models which will facilitate sensitivity analyses. Their main disadvantage is that they can only be applied to relatively simple flow (or transport) problems.

The main uses of analytical models are to:

- Assist in conceptual modelling
- Simulate flow and/or transport in simple physical settings (or where there are only one or two simple objectives)
- Simulate flow and/or transport for projects which have low risk of impact to VECs via groundwater
- Check results of the numerical model.

Analytical models should be used as a starting point in the assessment (e.g. during conceptual modelling) and before moving on to more sophisticated numerical models. Experimentation with analytical equations to examine the influence of changing parameter values on the model results is a vital exercise to gain an understanding of which are the key (i.e. the most sensitive) parameters and to develop a correct conceptual model.

For projects with relatively simple physical settings, or where the required accuracy of model predictions is not very high, analytical models may be adequate to simulate groundwater flow and/or contaminant transport. Analytical models may be the preferred choice of modelling for projects where there is insufficient monitoring data available, i.e. where the uncertainty due to data limitation is greater than the error caused by using a simplified analytical model. However, a lack of data does not justify reliance on an analytical solution alone; for complex systems, more data is required to support a more thorough modelling effort.

Where there are only one or two simple modelling objectives (i.e. determining drawdown or flow to a well), an analytical model may be adopted; however, where more modelling objectives are identified, a numerical model may provide more versatility.

Table 5-1: Advantages and Disadvantages of Analytical and Numerical Methods

	Advantages	Disadvantages
Analytical Methods	Calculation of the result using a calculator or spreadsheet can be very quick. With the aid of a spreadsheet the results of using hundreds of parameter variations can be determined very quickly.	They require most of the parameters to be constant in space and time (for example horizontal and vertical variations in hydraulic conductivity cannot be taken into account). There are exceptions to this rule but, in general, as soon as a parameter takes different values in different areas, the mathematics becomes too difficult to solve.
	Since the model can be written down as one, or a few, equations, the dependence of the result on each parameter can be seen clearly.	There may not be an analytical solution if the physics is complicated (e.g. if the Freundlich isotherm is thought to control sorption instead of the linear isotherm, then the transport equation becomes too difficult to solve).
	Analytical models provide a relatively quick method of examining contaminant transport systems. They can even be used to examine relatively complex systems by making a number of simplifying systems, provided it can be demonstrated that these assumptions do not affect the outcome of the modelling exercise.	They can generally be applied only to relatively simple flow systems, although by the careful use of simplifying assumptions more complex systems can be examined. In such cases a supporting argument should be presented to support the approach adopted and why it is reasonable.
	Techniques such as Monte-Carlo Analysis are more easily applied to analytical models than to numerical models, allowing uncertainty in model parameters to be taken into account.	
Numerical Methods	They provide more powerful tools to help in representing and understanding gfroundwater flow and contaminant transport because more aspects of the system behaviour can be represented. It should be noted that numerical models still require a number of assumptions or simplifications to be made about the system behaviour.	Time and cost involved in setting up and running the model.
	A higher degree of confidence can be attached to the model where it has been able to simulate observed groundwater flow and contaminant transport with time (this is assumes sufficient field observations are available for model calibration).	The tendency to believe that the model and the results are correct, because a numerical model has been used even though there may be considerable uncertainty about the system

From *UK Guide to Good Practice for the Development of Conceptual Models and the Selection and Application of Mathematical Models of Contaminant Transport Processes in the Subsurface, 2001*

The use of analytical solutions may also be adequate for projects with low risk of impact to VECs via groundwater. This includes projects where the project description includes mitigation options that reduce or even eliminate the contaminant source to such an extent that there is no (or only a very low) risk to VECs.

Analytical models may also be used by the modeller (or the reviewer) to check that numerical solutions produce approximately the right answer. It is very easy to mistype input for complex models and an analytic check can generate confidence in the numbers produced by a numerical model.

Note that analytical models may be used in conjunction with numerical models. For example, analytical models can be used to run preliminary sensitivity analyses on the groundwater system to define the most appropriate parameters for inclusion in a steady-state model. Furthermore, analytical transport solutions (e.g. Ogata Banks equation) may be used in conjunction with a numerical groundwater flow model. In this situation, the analytical transport equation could be used to estimate the breakthrough of a contaminant along an identified flow path which was determined by the numerical flow solution. The use of an analytical transport solution greatly reduces the computing time, in particular, if a detailed sensitivity analysis of various transport parameters is required.

5.3.1.3 Application to Natural Resource Projects

Analytical models are available for a wide range of flow and transport problems which are applicable to the natural resource industry, including:

- Groundwater flow in 1D and 2D (e.g. for conceptual modelling)
- Groundwater flow to a well (e.g. for pump test analysis, pit inflow estimates.)
- Groundwater flow to a trench (e.g. for inflow to collection ditches, underground mine.)
- Groundwater flow to a tunnel (e.g. for inflow to adits, underground workings.)
- Groundwater flow to an open pit (e.g. for inflow to open pit mine)
- Solute transport with 1D flow (e.g. for transport modelling along flow path).

Table 5-2 lists some useful analytical solutions commonly used in the resource industry. For more details on analytical solutions the reader is referred to Bear (1972), Domenico and Schwartz (1990) and Fetter (1992). A compilation of analytical solutions to common transport problems is provided in a software program (STANMOD) which was developed by the US Salinity Laboratory (Simunek et al., 1999) and can be downloaded from their website at http://www.ars.usda.gov/Services/.

Table 5-2: Useful analytical solutions for the resource industry

Application	**Solution**	**Reference (website)**
Confined Aquifer (General)		
Steady-State Flow (1D)	Darcy	Darcy, H. (1856) Les fontaines publiques de la ville de Dijon; Victor Dalmont, Paris. (http://www.edumine.com/xedumine/selectatool.asp)
Steady-State Flow in Small Basins (2D)	Tóth	Tóth J. (1962) A theory of groundwater motion in small drainage basins in Central Alberta. Journal of Geophysical Research 67:11, 4375-4387
Steady-State Radial Flow to a Well	Thiem	Thiem, Günther (1906) (in German). Hydrologische methoden. Leipzig: J. M. Gebhardt. pp. 56 (http://www.edumine.com/xedumine/selectatool.asp)
Transient Flow to a Well	Theis	Theis, Charles V. (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. Transactions, American Geophysical Union 16: 519–524. (http://www.edumine.com/xedumine/selectatool.asp)
	Cooper-Jacob	Cooper, H.H., and C.E. Jacob. (1946) A generalized graphical method for evaluating formation constants and summarizing well field history, Am. Geophys. Union Trans, Vol. 27, pp.526-534. (http://www.edumine.com/xedumine/selectatool.asp)
Unconfined Aquifer (General)		
Steady-State Flow	Dupuit-Thiem	Dupuit, J., (1863) Etudes theoriques et pratiques sur le mouvement des eaux dans les canaux decouverts et a travers les terrains permeables, 2eme edition; Dunot, Paris. (http://www.edumine.com/xedumine/selectatool.asp)
Steady State Radial Flow to a Well	Dupuit-Thiem	Dupuit, J., (1863) Etudes theoriques et pratiques sur le mouvement des eaux dans les canaux decouverts et a travers les terrains permeables, 2eme edition; Dunot, Paris. (http://www.edumine.com/xedumine/selectatool.asp)
Horizontal Flow to a Trench (with recharge)	Dupuit-Thiem	Dupuit, J., (1863) Etudes theoriques et pratiques sur le mouvement des eaux dans les canaux decouverts et a travers les terrains permeables, 2eme edition; Dunot, Paris. (http://www.edumine.com/xedumine/selectatool.asp)
Horizontal Flow to a Trench (no recharge)	Dupuit-Thiem	Dupuit, J., (1863) Etudes theoriques et pratiques sur le mouvement des eaux dans les canaux decouverts et a travers les terrains permeables, 2eme edition; Dunot, Paris. (http://www.edumine.com/xedumine/selectatool.asp)
BC Mining Applications		
2D Flow in Small Drainage Basins	Tóth	Tóth J. (1962) A theory of groundwater motion in small drainage basins in Central Alberta. Journal of Geophysical Research 67:11, 4375-4387
Inflow to Open Pit	Marinelli and Niccoli	Marinelli, F., Niccoli, W.L. (2000) Simple Analytical Equations for Estimating Ground Water Inflow to a Mine Pit.Ground Water 38:2, 311-342
Inflow to a Tunnel	Goodman	Goodman, R.E., Moye, D.G., Van Schalkwyk, A. and Javandel, I. (1965) Ground water inflow during tunnel driving, Eng. Geol., 2, pp. 39-56.
	Lei	Lei (1999) An analytical solution for steady flow into a tunnel. Ground Water 37:1, 23-25
Groundwater Mounding	Hantush	Hantush, M.S.,(1967) Growth and decay of groundwater mounds in response to uniform percolation. Water Resources Research, v. 3, p. 227–234. as presented in analytical form by Carleton, G.B. (2000) Simulation of Groundwater Mounding beneath Hypothetical Stormwater Inflitration Basins. USGS Scientific Investigations Report 2010-5102
1D Solute Transport	Ogata-Banks	Ogata, A. & Banks, R.B. (1961) A solution of the differential equation of longitudinal dispersion in porous media. U.S. Geological Survey Professional Paper 411-A. (http://www.ars.usda.gov/Services/docs.htm?docid=8960)
2D & 3D Equilibrium Solute Transport	various	Leji and Bradford (1994) (http://www.ars.usda.gov/Services/docs.htm?docid=8960)

5.3.2 Numerical Models

5.3.2.1 Definition

A numerical model uses numerical methods to solve the governing equations of groundwater flow and/or contaminant transport. In distributed numerical models, space and time are divided into discrete intervals (as illustrated by Figure 5-4 and 5-5) where for each model grid cell, parameter values are defined including hydraulic conductivity, porosity, aquifer thickness, initial contaminant concentration, etc.

Numerical models enable more complex systems to be represented than can be represented by analytical models. Furthermore, numerical models may allow for multiple modelling objectives to be addressed in parallel. Numerical models still require simplifications to be made about system behaviour.

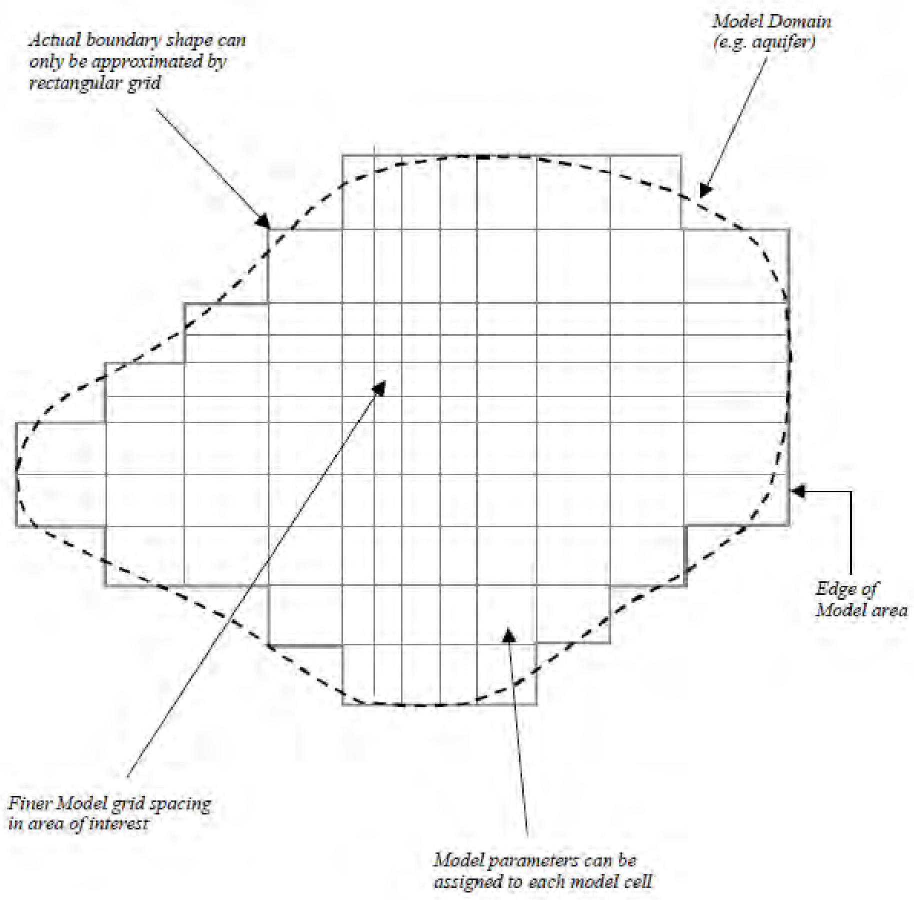


Figure 5-4: Illustration of finite-difference approach (reproduced from NGCLC, 2001)

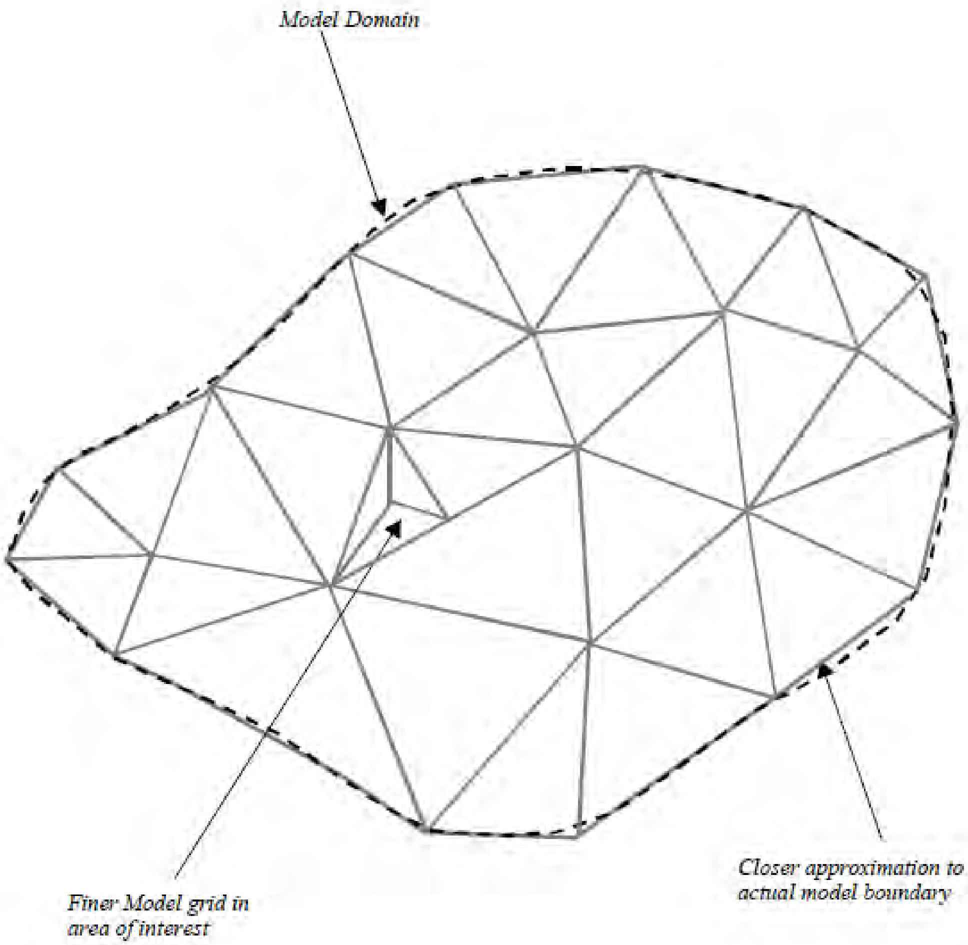


Figure 5-5: Illustration of finite-element approach (reproduced from NGCLC, 2001)

5.3.2.2 Model Use

Table 5-1 lists the advantages and disadvantages of analytical models vis-à-vis numerical models. The main advantage of numerical models is that different parameter values can be assigned to each cell, so that lateral and vertical variations in property values can be taken into account. The geometry of the model can be designed to reflect the geometry of the system. In addition, models can be constructed that include more than one layer; this enables multi-layered aquifers to be represented. For time variant models, model inflows (e.g. recharge and its contaminant concentration) and outflows (e.g. groundwater abstractions) can be specified for each model time step.

Their main disadvantage is that numerical models can be costly and time-consuming. Another potential disadvantage is that the model complexity reduces the transparency of the model calculations and/or can mask the remaining model uncertainty.

Numerical models will generally be applicable where:

- Previous modelling studies (or conceptual modelling) using simple analytical models have shown that a more sophisticated approach, such as incorporating spatial variability, is required.
- The groundwater regime is too complex to be robustly represented by an analytical model.
- The required model accuracy (as defined by the model objectives) requires the use of a numerical model.
- Processes affecting contaminant transport cannot be adequately represented by simple transport equations.
- An analytical model is inadequate for the design of mitigation measures, e.g. in determining the optimal location and pumping rate for boreholes in a pump and treat scheme.

Numerical models should be considered where the scale and importance of the problem warrant the use of a more sophisticated approach. For such sites, the scale of the problem should demand detailed site investigations which should provide sufficient information to allow the construction of a numerical model.

Numerical models should not be used as an alternative to data collection. Instead, appropriate use of a numerical model may require and/or help guide additional data collection so that the model can be properly parameterized and calibrated as well as support system interpretation.

5.3.2.3 Application to Natural Resource Projects

Numerical models are versatile and flexible with respect to model domain, boundary conditions and other stresses and can be used to simulate almost any groundwater flow and contaminant transport problem related to natural resource projects in British Columbia (See section 3).

A range of different numerical models (also referred to as “modelling codes” or simply “codes”) are available to cover specific aspects of groundwater flow and contaminant transport (see Section 5.4 below).

Some numerical models only solve the equations for groundwater flow (“flow models”) while other models solve only the equations for contaminant transport (“transport models”) and yet others solve both sets of equations (“flow and transport models”). Some modelling codes are very versatile while other modelling codes have a narrower range of application (e.g. 2D cross-sectional models) or specialize on certain aspects of groundwater flow (e.g. variably saturated flow, density-dependent flow).

A more detailed review of modelling codes suitable for use in the resource industry is given in Section 5.4 below.

5.3.3 Analytic Element Models

5.3.3.1 Definition

An analytic element model uses superposition of closed-form (analytical) solutions to the governing differential equation of groundwater flow to approximate both local and (near-field) and regional (far-field) flow. Hence, analytic element models do not require grid discretization or specifications of boundary conditions on the grid perimeter (Hunt et al., 1998).

These characteristics allow for representation of large domains that include many hydrogeologic features outside the immediate area of interest (i.e. far-field) and easy modification of the regional flow field by adding analytic elements representing regional hydrologic features.

5.3.3.2 Model Use

Analytic element models are well-suited for use as screening models (Hunt et al., 1998). Analytic element models can be used to develop conditions on the grid perimeter for a smaller numerical model, similar to the process of telescopic mesh refinement (TMR). The advantage over traditional TMR using finite difference models is that this method: (i) allows easy addition of far-field elements until the far field is correctly simulated; and (ii) avoids discretization problems that can occur in large-scale models with large cell/element sizes.

The major limitation of analytic element models is that the method is only computationally efficient for steady-state flow in large aquifers where the vertical flow component can be ignored.

5.3.3.3 Application to Natural Resource Projects

The analytic element method is not commonly used by the consulting community to study natural resource projects, due to lack of easy-to-use software codes, familiarity by the model practitioners, and/or its limitations (only applicable to 2D steady-state flow).

5.4 NUMERICAL MODELLING TOOLS

5.4.1 Solution Methods

Several numerical methods are available to solve the governing equations for groundwater flow and contaminant transport, including (NGCLC, 2001):

- Finite difference method (flow & transport)
- Finite element method (flow & transport)
- Eulerian methods such as TVD (transport)
- Lagrangian method (transport)
- Mixed Eulerian-Lagrangian method (transport).

The following sections provide brief overview of the two common methods to solve groundwater flow and transport. The solution methods available to specifically solve solute transport are discussed further in Section 9.

5.4.1.1 Finite Difference Method

Finite Difference Method (“FDM”) is the most commonly used approach in numerical groundwater flow modelling. For most finite difference models the space and time co-ordinates are divided on a rectangular grid (Figure 5-4), and model parameters (such as hydraulic conductivity, aquifer thickness etc.) are specified for each model grid cell. The flow and transport equations are solved by direct approximation. The grid spacing represents the degree of accuracy of the model in representing lateral or vertical changes in the property values that describe the system. Finite difference methods have the advantage of being relatively simple to use, but have the disadvantage of not accurately representing irregular boundaries; also it is difficult to change the grid spacing to provide greater precision in areas of interest.

5.4.1.2 Finite Element Method

In the Finite Element Method (“FEM”) the spatial domain is divided into a mesh of elements, generally of triangular or quadrilateral shape (Figure 5-5). Variation in a model parameter across the model element is normally approximated by a polynomial function. This technique provides greater flexibility than finite difference methods in representing the model domain, particularly complex geological boundaries. The model mesh can easily be modified to provide greater precision in areas of interest, although complex meshes require software tools for their management. Finite element models are less susceptible to numerical dispersion than finite difference models, but for the same number of elements/cells the computing requirements are higher.

5.4.2 Model Codes

A groundwater modelling code is defined as a computer code that solves a groundwater flow or contaminant transport problem. The computer code facilitates input of relevant model input parameters (e.g., model grid, aquifer parameters, boundary conditions.) and solves the groundwater flow or contaminant transport problem. Most model codes provide options for viewing the model output (e.g. head solutions in space and time; groundwater budget etc.).

Table 5-3 lists commercially available groundwater modelling codes commonly used in the groundwater industry in North America. The following codes are routinely used in the resource industry in British Columbia and are discussed below in more detail:

- MODFLOW (flow)
- MODFLOW SURFACT (flow and transport)
- MODPATH (particle tracking)
- MT3DMS (transport)
- SEEP/W (flow)
- FEFLOW (flow & transport).

The list of modelling codes described in Table 5-3 and discussed here does not include all available modelling codes. Many other groundwater modelling codes exist and new groundwater modelling codes will undoubtedly be developed in the future. The groundwater modeller is encouraged to stay abreast of the development of new computer codes to find the code most suitable to meet the project objectives.

Table 5-3: Commonly used numerical groundwater modelling codes in North America (adapted from MDBC, 2001)

	MODFLOW	**MODFLOW-SURFACT**	**MT3D(MS)**	**SEEP/W & VADOSE/W**	**FEFLOW**	**HYDRUS 2D/3D**	**FEMWATER**	**SUTRA**
Model Type	Saturated 3D Flow	Saturated/Variably Saturated 3D flow and Solute Transport	3D Solute Transport	2D Variably Saturated Flow	Saturated/Variably Saturated 3D flow and Solute Transport	2D/3D Variably Saturated Flow	Saturated/Unsaturated 3D flow and Solute Transport	Saturated 3D flow and Solute Transport; 2D Variably Saturated Flow
Developer, Support	USGS, most developers	HydroGeoLogic Inc. (based on USGS Modflow)	US EPA, Papadopoulos & Associates Inc., Hydrology Group at University of Alabama	GeoSlope Int'l	DHI-WASY GmbH	US Salinity Laboratory	US Army Corps of Engineers / US EPA	USGS
Supplier	USGS	HydroGeoLogic Inc.	University of Alabama	GeoSlope Int'l	DHI-WASY GmbH	PC-Progress	US EPA	USGS
Cost*	Free	$2,500 to $6,000	Free to $700	$4,000 to $5,000	$4,000 to $8,000	$2,000 to $4,000 (3D)	Free	Free
Solution Method	FD	FD	FD	FE	FE	FE	FE	FE
Stream-Aquifer Interaction	Excellent	Excellent	MT3D uses MODFLOW for flow solution	No	Excellent	Reasonable	Reasonable	Reasonable
Unsaturated Capability	No	Yes (handles multiple perched water tables)	No	Yes	Yes	Yes	Yes	Yes
Density Coupled	Yes (SEAWAT version)	Yes (SEAWAT version)	Yes (SEAWAT version)	No	Yes	No	Yes	Yes
GUI (refer separate table)	VM, GMS, GWV, PMWin	GV (Compatible with PMWin, VW, GMS)	VM, GMS, GV, PMWin	Self-contained	Self-contained	Self-contained	Can use GMS	Self-contained
Case Studies (Verification)	Yes	Yes?	Yes	Yes	Yes	Yes	No	Yes
Comments	Industry-leading numerical flow modeling package	improved wetting/drying capabilities; can be integrated with streamflow models	Industry-leading solute transport model; offers wide range of transport solution options	SEEP/W popular for seepage problems; VADOSE/W offers improved soil-atmosphere model	very versatile flow code with wide range of boundary conditions;			
Internet Reference	http://water.usgs.gov/nrp/gwsoftware/modflow.html	http://www.hglsoftware.com/Modflow_Surfact.cfm	http://hydro.geo.ua.edu/mt3d/	http://www.geo-slope.com/products/seepw2007.aspx	http://www.feflow.info/	http://www.pc-progress.com/en/Default.aspx?hydrus-3d	http://www.epa.gov/ceampubl/gwater/femwater/	http://water.usgs.gov/nrp/gwsoftware/sutra.html

*Estimate based on single-user licence with range of basic modules / add-ons; does not include cost of GUI unless noted as *Self-contained*).

5.4.2.1 MODFLOW

MODFLOW is a three-dimensional finite-difference ground-water model that was developed by the USGS and first published in 1984 (McDonald and Harbaugh, 1984). This code has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model. The most recent version is MODFLOW-2005 (Harbaugh, 2005) but the earlier version MODFLOW-2000 (Harbaugh et al., 2000) is still in common use.

MODFLOW simulates steady and non-steady (“transient”) flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined (“convertible layer”). Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary.

MODFLOW has a built-in solute transport function (MOC-3D). MODFLOW is more commonly used in combination with MT3D, another modular solute transport code.

MODFLOW is the most commonly used groundwater code world-wide and many graphical user-interfaces (GUI) have been developed to support its use (see below). This code is well-documented and verified.

The main advantages of MODFLOW are that the code is robust, easy to use, and versatile. In addition, the availability of powerful GUIs greatly facilitates the model setup (pre-processing) as well as interpretation and visualization of model output (post-processing). The MODFLOW code also enables the modeller to extract detailed water balance information from the model (using the FLOWBUDGET subroutine) which greatly assists with model interpretation and trouble shooting.

The main limitations of MODFLOW include: (i) the inefficient use of rectangular grids to represent complex geometries; and (ii) convergence problems related to wetting/drying of cells near the water table. The first limitation is common to all finite-difference models and can be dealt with by using a denser grid spacing (which is no longer a major limitation with increased processing power).

The second limitation is more important, in particular for unconfined flow problems in steep terrain. When solving an unconfined flow problem, MODFLOW checks the saturated thickness of the uppermost (active) unconfined (or convertible) layer. If the simulated water table in a given cell falls below the bottom elevation of the cell, this cell is made inactive (or “dry”), In subsequent iterations, this cell may be made “active” again (i.e. “wetted”). This wetting capability can cause significant convergence problems, in particular in steep terrain where the water table may interact with several model layers.

Note that the USGS has recently released a new MODFLOW code that can handle the drying/wetting issue (MODFLOW-NWT). At present, this version is still not included in most GUIs for MODFLOW and is therefore not widely used.

In many MODFLOW applications to natural resource projects (where steep topography is common) this problem is avoided by assuming confined conditions. This simplification may be adequate for some situations (e.g. baseline conditions) but can result in significant error in flow predictions (e.g. in inflow to an open pit).

These guidelines generally recommend the use of MODFLOW for most natural resource projects. More sophisticated codes (such as MODFLOW SURFACT or FEFLOW) may be required for projects with complex geometry and/or in steep topography (see below).

5.4.2.2 MODFLOW SURFACT

MODFLOW-SURFACT is a proprietary code developed by Hydrogeologic Inc. to simulate saturated/unsaturated groundwater flow and solute transport (HGL, 2008). MODFLOW-SURFACT was developed to overcome numerical difficulties encountered with MODFLOW, primarily related to the drying/wetting problem.

MODFLOW-SURFACT solves the fully 3D saturated/unsaturated groundwater flow equations, or alternatively, solves enhanced equations for performing unconfined simulations to rigorously model desaturation/resaturation of aquifers.

Additional improvements offered by the MODFLOW-SURFACT code include:

- Use of a curvilinear grid for efficiently fitting irregular domain geometries
- Additional boundary conditions (seepage face, unconfined recharge)
- Adaptive time stepping and restart options.

The primary advantage of MODFLOW-SURFACT is the handling of complete desaturation and resaturation of grid blocks and accurate delineation and tracking of the water table position. These additional abilities may be of importance in some natural resource projects, in particular where unconfined conditions are encountered in steep terrain (or is induced by mine dewatering).

These guidelines recommend the use of MODFLOW-SURFACT for natural resource projects where the vertical component of unconfined groundwater flow is an important modelling objective.

5.4.2.3 MODPATH

MODPATH is a particle-tracking post-processing package that was developed to compute three-dimensional flow paths using output from steady-state or transient ground-water flow simulations by MODFLOW. MODPATH uses a semi-analytical particle tracking scheme that allows an analytical expression of the particle's flow path to be obtained within each finite-difference grid cell.

MODPATH calculates pathlines and travel times of groundwater flow (and solutes dissolved in groundwater). Particle tracking can be used to draw flow nets, determine recharge zones and/or capture zones, and to estimate travel times of conservative contaminants of concern (see Section 9).

MODPATH is the most common particle tracking code in the groundwater industry. It is useful as a visualization tool to help understand flow patterns in simulated ground-water flow systems. It is useful for delineating sources of water to discharge sites and aquifers in systems simulated with MODFLOW.

This code is efficient, very easy to use and provides good visualization options (e.g. time markers). These guidelines recommend the use of MODPATH in conjunction with MODFLOW for particle tracking.

5.4.2.4 MT3DMS

MT3DMS is a comprehensive three-dimensional numerical model for simulating solute transport in complex hydrogeologic settings (Zheng and Wang, 1999). MT3DMS has a modular design that permits simulation of transport processes independently or jointly. MT3DMS is capable of modelling advection in complex steady-state and transient flow fields, anisotropic dispersion, first-order decay and production reactions, and linear and nonlinear sorption.

MT3DMS is linked with the USGS groundwater flow simulator MODFLOW, and is designed specifically to handle advectively-dominated transport problems without the need to construct refined models specifically for solute transport.

MT3DMS combines three major classes of transport solution techniques in a single code, namely, the standard finite difference method; the particle tracking based Eulerian-Lagrangian methods; and the higher-order finite-volume total-variation-diminishing (TVD) method. This unique range of solution techniques allows the user to solve a wide variety of transport problems ranging from advection-dominated (e.g. using TVD) to mixed advection-dispersion problems (EL methods) to dispersion dominated problems (FD).

MT3DMS is implemented with an optional dual-domain formulation for modelling mass transport in highly heterogeneous porous media or fractured media with a mobile domain (where solutes are moved by groundwater flow) and an immobile domain (where no groundwater flow occurs and solutes only move by diffusion).

This code is very well documented and is supported by all major GUIs developed for MODFLOW.

These guidelines recommend the use of MT3DMS for the simulation of solute transport problems of natural resource projects (in conjunction with MODFLOW).

5.4.2.5 SEEP/W and VADOSE/W

SEEP/W is a finite-element code for analysis of 2D seepage and excess pore-water pressure dissipation problems in porous media (Geoslope, 2007). SEEP/W can simulate steady-state confined and unconfined flow, transient flow, 2-D flow in a cross-section or in plan view, and 3D axisymmetric flow.

SEEP/W can simulate both saturated and unsaturated flow, a feature that greatly broadens the range of problems that can be analyzed. In addition to traditional steady-state saturated flow analysis, the saturated/unsaturated formulation of SEEP/W makes it possible to analyze seepage as a function of time and to consider such processes as the infiltration of precipitation. The transient feature allows you to analyze such problems as the migration of a wetting front and the dissipation of excess pore-water pressure.

Boundary condition types available in SEEP/W include total head, pressure head, or flux specified as a constant or a function of time; transient flux as a function of computed head; and review and adjustment of seepage face conditions.

SEEP/W is commonly used for engineering problems, in particular for assessment of seepage and associated pore pressures in tailings dams. However, this code is also capable of simulating variably saturated flow in natural aquifer systems (e.g. perched layers), but only in a 2D cross-sectional domain. Therefore, seepage from the lens in the transverse direction would need to be negligible, which may not be reasonable for smaller lenses.

SEEP/W has an easy-to-use graphical user interface (GUI) which facilitates setup of the model (mesh construction, model parameterization) and visualization of the model output (flow net, pore pressures etc.).

VADOSE/W has similar capabilities to those of SEEP/W but has a more rigorous algorithm to describe the soil-atmosphere interactions at the ground surface, including the simulation of actual evapotranspiration and net infiltration using atmospheric inputs.

These guidelines recommend the use of SEEP/W and VADOSE/W for the assessment of 2D seepage problems involving engineering structures (e.g. tailings dams) and 2D infiltration problems, respectively.

5.4.2.6 FEFLOW

FEFLOW is a versatile finite-element code that solves the following groundwater flow and contaminant transport problems (DHI-WASY, 2007):

- Transient or steady-state flow (3D)
- Saturated and unsaturated flow
- Multiple free surfaces (perched water table)
- Density-dependent flow (salt water intrusion)
- Contaminant and heat transport.

FEFLOW has a comprehensive selection of graphical tools for building the finite element mesh, assigning property zones and setting boundary conditions. The modelling platform includes state-of-the-art 3-D visualization of modelling outputs.

The main advantages of FEFLOW include: (i) versatility of code to solve different flow and transport problems; (ii) flexibility in model discretization due to use of the finite element method; and (iii) flexibility in formulation of boundary conditions. This flexibility in model discretization and boundary conditions can be very useful when simulating complex flow problems (e.g. mine developments in structurally controlled bedrock; progressive excavation of an open pit and/or underground mine workings).

FEFLOW can solve groundwater flow in the following modes:

- Unconfined (“Phreatic”) mode
- Confined mode
- Variably saturated mode.

The use of the phreatic or the variably saturated option can lead to numerical instability and/or non-convergence if the water table crosses model layers (a common problem at project sites with steep topography). The assumption of a confined aquifer may be required to get a stable solution for problems with steep terrain (similar to MODFLOW).

Other limitations of the FEFLOW code which the modeller (or reviewer) should be aware of include:

- FEFLOW has limited capabilities to evaluate the water balance (e.g. change in storage is not provided in the water balance; flux section tool provides only approximate internal fluxes).
- FEFLOW does not allow pinching out of model layers and will simulate “artificial” flow through layers above the water table in phreatic mode (using the saturated hydraulic conductivity).
- Phreatic conditions may produce artificial water if residual water depth in “dry elements” is set too large.

- The transport algorithm of FEFLOW is prone to numerical oscillations and/or numerical dispersion requiring a high degree of horizontal and/or vertical discretization (which can be prohibitive for regional models).

The use of FEFLOW requires significant modelling expertise, including an in-depth understanding of finite-element methods and the FEFLOW code itself. The flexibility of the FEFLOW code makes it a powerful tool but a difficult one to use. For this reason, the use of FEFLOW is only recommended for experienced modellers.

These guidelines recommend the use of FEFLOW for complex natural resource problems in which complex geometries and/or complex boundary conditions will have to be simulated. FEFLOW is suitable for density-dependent groundwater flow problems (e.g. saltwater intrusion problems and/or deep groundwater flow involving brines).

5.4.2.7 Other Codes

As mentioned at the beginning of this section, the groundwater modelling codes listed in Table 5-3 and described above are those most commonly used by the industry in British Columbia. This list is not meant to be prescriptive and other groundwater modelling codes are available and may be equally, or better, suited for a given groundwater flow and solute transport problem.

If other, less common modelling codes are used, the user should confirm and document that the code in question has been adequately verified (see Section 5.4.4 below).

5.4.3 Graphical User Interface (GUI)

Most proprietary modelling codes come with a built-in Graphical User Interface (GUI) that improves model parameterization (pre-processing) and visualization of model output (post-processing).

Some modelling codes, namely MODFLOW and MT3DMS, include commercial graphical user interfaces that are commercially available. Table 5-4 summarizes the most common GUIs for MODFLOW/MT3DMS.

The capabilities and limitations of a GUI can significantly influence the outcome of a modelling study and should therefore also be considered when selecting a mathematical code for a given modelling objective. For example, some GUIs allow the use of automated parameter estimation while others do not support this option, thus limiting the options for model calibration.

Table 5-4: Common Graphical User Interfaces (GUI) for MODFLOW/MT3DMS (adapted from MDBC, 2001)

Package	**Groundwater Vistas**	**MODFLOW-SURFACT**	**Processing MODFLOW**	**Visual MODFLOW**	**Groundwater Modeling System**
Abbreviation	**GV**	**MS-VMS**	**PMWin**	**VM**	**GMS**
Approx. Cost	$1,400	$6,000	$1,600	$1,600	$3,000 to $6,000
Developer, Support	ESI	HydroGeoLogic	Chiang & Kinzelbach	Waterloo Hydrogeologic	Aquaveo
Supplier	ESI	ESI	Developer	Waterloo Hydrogeologic	EMSI
Unsaturated Capability	Yes, with MODFLOW-SURFACT	Yes (Richard's equation), with air phase flow simulation			
Density Coupled	Yes, with SEAWAT	Yes, with SEAWAT	PMWin Density Package	Yes, with SEAWAT	Yes, with SEAWAT
Fracture Flow	No	Yes	No	No	No
Solute Transport and Particle Tracking	MT3DMS, MODPATH	MT3DMS, MODPATH	MT3DMS, MT3DMS, MOC3D, PMPath99	MT3DMS, MODPATH	MT3DMS, ModPath, RT3DMOC3D, SEAM3D
Supports (additional purchase required)	MT3DMS, RT3D, MOC3D, Path3D, MODFLOWT, MODFLOW-SURFACT	MT3DMS, RT3D, MOC3D, Path3D		MT3DMS, ModPath	MT3DMS, ModPath, RT3D, MOC3D, SEAM3D
Auto-Calibration	Supports PEST, UCODE	Supports PEST, UCODE	Bundled with Pest (Lite), UCODE	Supports WinPest	Supports PEST
Presentation and SURFER Compatibility	Import/export SURFER grid and data files. Exports DXF, HPGL, BMP. 3D animation with TecPlot.	Import/export SURFER grid and data files. Exports DXF, HPGL, BMP. 3D animation with TecPlot.	Import SURFER grid, geo-referenced raster graphics. Export SURFER data files, DXF, HPGL, BMP.	Import/export SURFER grid & data files. Export DXF, EMF, ESRI shape file. 3D animation with Visual Groundwater.	GIS capability (ArcInfo, ArcView), import/export DXF (AutoCAD or MicroStation); 3D subsurface modeling
Telescopic Mesh Refinement	Yes	Yes	Yes	No	Yes
On-screen Views	Plan and cross-section	Plan and cross-section	Plan in flow model, plan and cross-section in particle tracking. Some animation. Velocity vectors.	Plan and cross-section	Plan and cross-sections of heads, fence diagrams; drawdowns and velocity vectors, and animation
Parameter Sensitivity Analysis	Automated	Automated	No	No	Limited
Reference	http://www.groundwatermodels.com/	http://www.hglsoftware.com/Modflow_Surfact.cfm	http://www.pmwin.net/pmwin5.htm	http://www.swstechnology.com/groundwater-software/groundwater-modeling/visual-modflow	http://www.aquaveo.com/gms-intro

The following aspects of a GUI should be considered by the modeller during model selection:

- General
    - Reliability and stability of GUI
    - Technical support (User support and product development)
    - Flexibility in solution techniques (especially important for solute transport)
    - Support of automated parameter estimation (e.g. PEST).
- Pre-processing capabilities
    - Compatibility with GIS and/or ACAD
    - Ease of definition (and later adjustment) of boundary conditions
    - Ease of model discretization (and later regridding/remeshing)
    - Ease of implementation of complex geometries (e.g. boundary conditions along arcs,
- Post-processing capabilities
    - Support for model calibration (water balance output, visualization of residual error in scatter plots, histograms, maps etc.)
    - Ease & automation of modelling outputs (e.g. to Excel).

The selection of the most appropriate GUI depends on the project specifics and the modelling objectives. The capabilities and limitations of the GUI should be carefully considered by the modeller at the outset of the project. If limitations in the GUI are encountered at a later stage during the modelling study, the modeller should be prepared to switch to another GUI (and/or mathematical code).

These guidelines recommend the use of flexible GUIs which enable the user to easily adjust the conceptual model (domain boundaries, boundary conditions, zonation) and regrid/remesh the domain (e.g. GMS). This flexibility helps the modeller to start with a simpler model and gradually build-up the complexity of the model (rather than starting out with a very complex model).

5.4.4 Code Verification

Groundwater modelling codes used for the assessment of potential impacts by natural resource projects should be verified.

The process of code verification involves a check that the code is free of errors, i.e. mathematical equations are appropriately coded and the modelling results are correctly output. At a minimum, code verification should include a comparison of the modelling results against analytical solutions (for simplified problems). In addition, model verification may include a comparison of the modelling results against a numerical solution obtained using other (preferably verified) modelling codes (for more difficult problems).

All modelling codes (and supporting GUI) listed in Table 5-3 and described above have been extensively verified. However, continuous upgrading of modelling codes and/or improvements of the GUIs can introduce errors that may not be readily apparent. If numerical problems are suspected or encountered then selected modelling results (for example the calibrated model) could be checked using different modelling codes (e.g. MODFLOW and FEFLOW). A good agreement of modelling results using independent modelling codes will ensure that modelling results are not influenced by input errors and/or code selection.

The modeller should document all code verification completed as part of the QA/QC of the modelling study.

5.5 CODE SELECTION PROCESS

Figure 5-6 summarizes the process of selecting the appropriate mathematical model for groundwater flow and solute transport. The first step in the process is to determine whether the groundwater flow regime can be represented by an analytical model or whether a numerical model is required.

If an analytical solution is not available (or not sufficiently accurate) a numerical flow code should be selected. During the selection the capabilities and limitations of the available flow codes (see Section 5.4) should be compared to the defined modelling scope (see Section 5.2) and the code most suitable should be selected. In many instances, alternative codes are available to solve the same flow problem. In this case the final code selection may be influenced by other factors such as the availability of the code and/or the familiarity of the modeller with the code and GUI.

A similar selection process is then repeated for the contaminant transport problem (Figure 5-6). The first step in this selection process is to determine whether an analytical solution exists for the transport problem. Note that the use of a numerical flow model does not necessarily require the use of a numerical transport model. For example, a complex three-dimensional flow model may provide for the definition of a (simplified) 1D flow path. An analytical transport solution may then be applied to simulate transport along this 1D flow path assuming average hydraulic properties.

If no analytical transport solution is available (or not sufficiently accurate), a numerical transport code should be selected. Again, the capabilities and limitations of the available transport codes (see Section 5.4) should be compared to the defined modelling scope (see section 5.2) and the code most suitable should be selected.

As discussed in Sections 5.2.5 and 5.2.6, these guidelines recommend a phased approach to transport modelling which may require the use of different transport models, ranging from simple (conservative) particle tracking codes to sophisticated solute transport modelling codes.

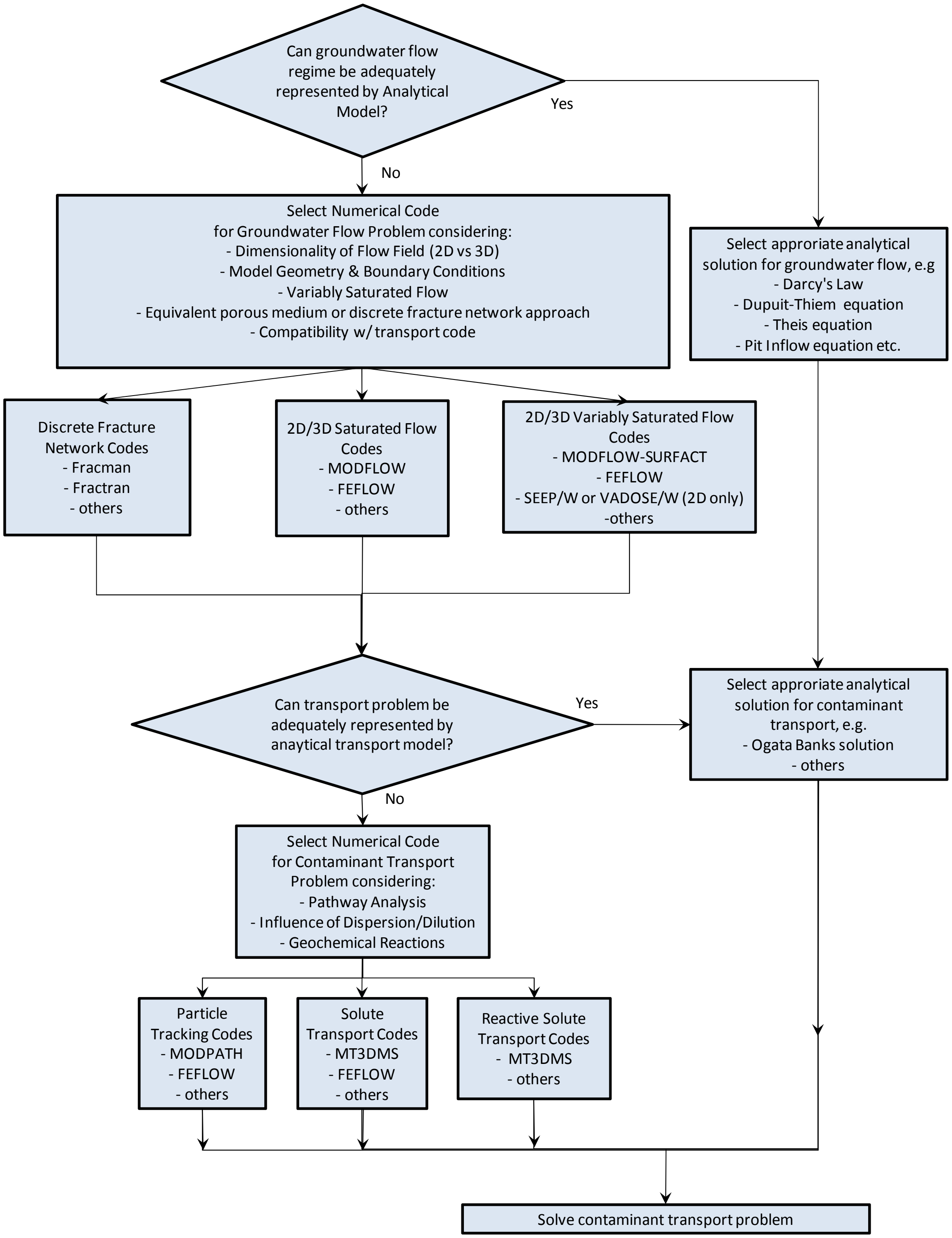


Figure 5-6: Flow chart illustrating selection of mathematical model.

5.6 CASE STUDIES

5.6.1 Case Study 1: Open Pit Mine

5.6.1.1 Overview

Case Study 1 illustrates the use of multiple mathematical models (and codes) to assess the potential impacts of a proposed open pit mine. A more detailed description of this case study is provided in Appendix C.

The following models were developed to address modelling objectives:

- A 3D basin-wide groundwater flow model to assess regional groundwater flow and pit inflow
- An analytical model (Darcy calculations) to estimate pit inflow along a fault
- A 2D (cross-sectional) variably-saturated flow model to assess seepage from the TSF
- A 3D local flow model to evaluate seepage from the TSF to local creeks (VEC).

The use of multiple models to address various groundwater flow aspects of the project (which differ in scale and complexity) is good modelling practice and is generally recommended.

5.6.1.2 Basin-wide model

Regional groundwater flow was conceptualized to be three-dimensional. The model domain covers an area of about 40 km^2 and is bounded primarily by the natural groundwater divides formed by creeks to the north, south, and east, and by bedrock topography to the west (Figure 5-7). Vertically, the model was discretized into five hydrostratigraphic layers representing glacial outwash, till, and bedrock.

The three-dimensional finite difference code MODFLOW-SURFACT was selected for the basin-wide modelling for two primary reasons:

- The code integrates groundwater and surface water flow systems, and;
- The code employs an updated wetting/drying function which minimizes convergence problems typically associated with MODFLOW simulations in steep terrain with steep groundwater gradients.

Convergence problems were encountered with MODFLOW-SURFACT and the model had to be run assuming confined conditions (while applying recharge). This illustrates the difficulty of modelling unconfined groundwater flow in steep terrain.

The model was first run with steady state conditions (using no-flow boundaries coinciding with the watershed boundaries) to evaluate regional flow and then run with transient conditions to assess groundwater contribution to streamflow under low recharge conditions.

The 3D basin-wide model was used to predict inflows to the open pit. Note that the assumption of confining conditions (required for the regional model) results in an overestimate of pit inflow estimates.

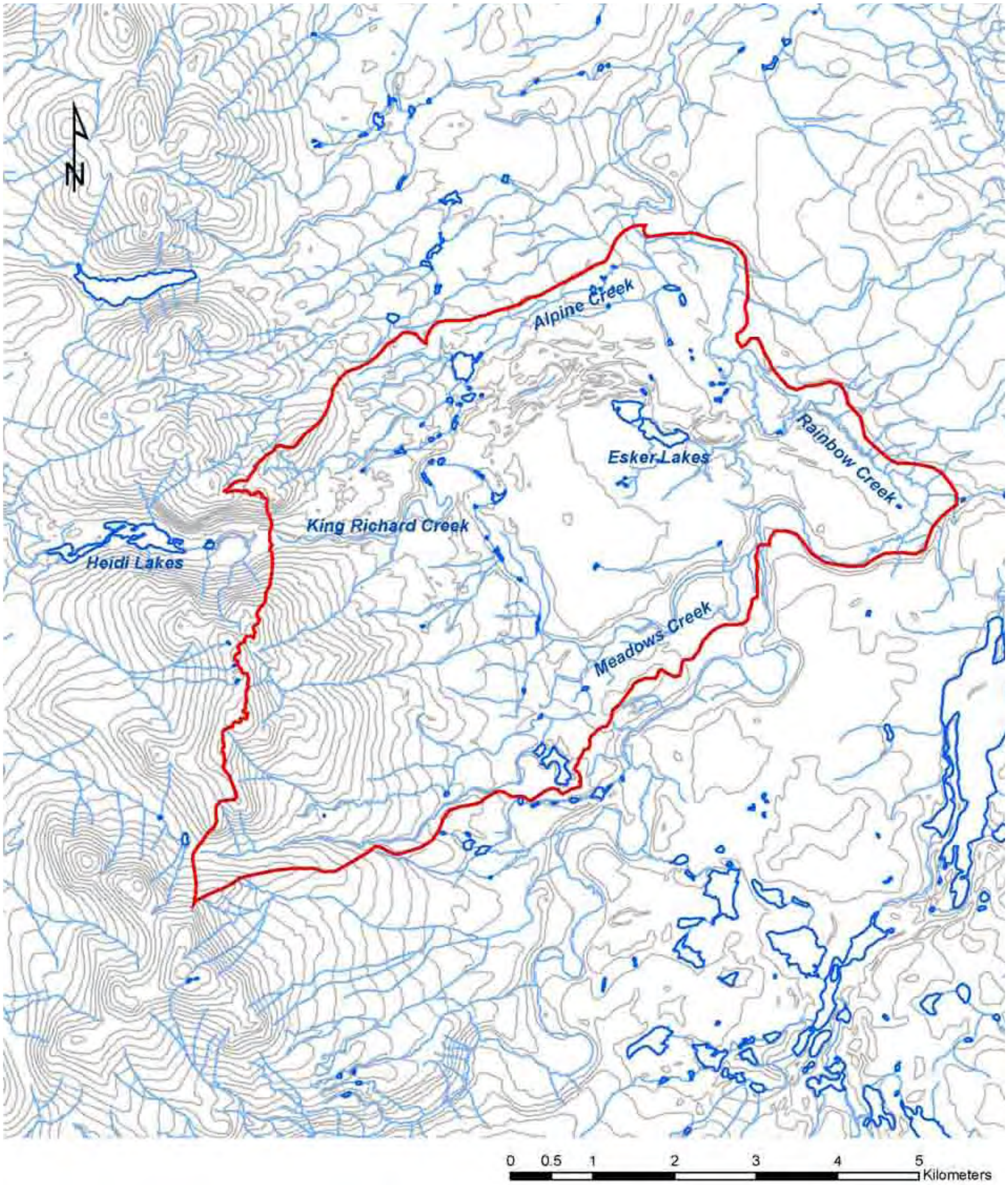


Figure 5-7: Domain of 3D basin-wide model Using MODFLOW-SURFACT), Case Study 1

5.6.1.3 Analytical Model for Pit Inflow

As fault zones were intersected during drilling in the open pit area, a Darcy-based analytical approach was used to conservatively estimate the discharge from an intersecting fault zone. For this method, flows into the pit were comprised of two components – lateral flow towards the fault and flow along the fault. These two components of flow were assumed to originate from recharge due to precipitation. Radial inflow to the pit through the surrounding lithology, which would reduce flows toward the fault, was not considered.

The estimated pit inflow along the potential fault was summed with the numerical inflow calculation and the estimate of TSF seepage contribution to determine a conservative pit inflow estimate.

5.6.1.4 TSF 2D Seepage Model

A series of two dimensional cross-sectional seepage models were created to meet the following objectives:

- Estimate seepage using a range of hydraulic conductivity values for the glacial foundation materials (sensitivity analysis)
- Identify key flow pathways
- Estimate groundwater recharge under unsaturated conditions.

The finite-element code VADOSE/W was selected for its applicability to variably saturated flow problems.

The 2D model (see Figure 5-8) incorporates hydrostratigraphic units consistent with the basin-wide model and materials representing the gradation of tailings and TSF structural elements (i.e. the core, filter, and shell of the TSF dam).

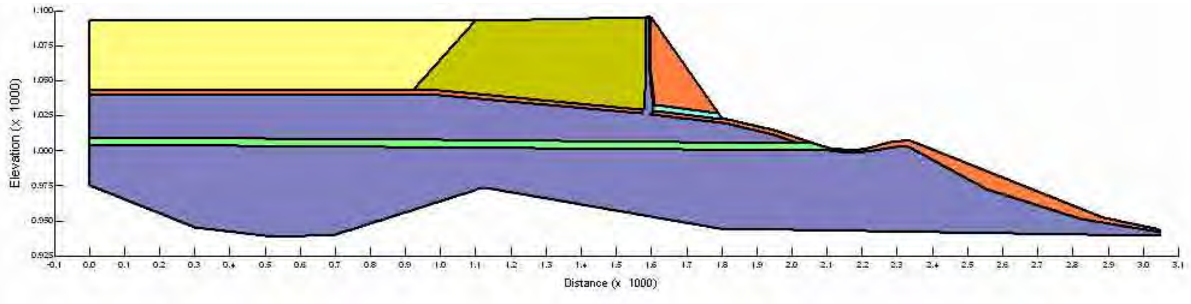


Figure 5-8: 2D cross-sectional model to assess TSF seepage (using Vadose/W), Case Study 1.

The seepage estimates determined with the 2D cross-sectional models were summed and used as recharge inputs to a 3D TSF model. This approach is conservative in a sense that the 2D model cannot account for radial flow under the TSF. Generally, flow from a relatively small pond area will radiate outwards to a larger discharge area. Summing up a series of 2D sections will cause an overlap in the recharge areas, thereby overestimating recharge.

This approach illustrates the appropriate use of conservative assumptions to simplify a 3D flow problem to a 2D flow problem.

It should be noted that the use of a conservative geometry assumption (here 2D) does not necessarily result in conservative seepage estimates. In many cases, the uncertainty in hydraulic properties of the mine waste and/or underlying aquifer material is much greater than the geometry effects. This is particularly true for variably saturated flow problems where unsaturated hydraulic properties (such as soil water characteristic curves) are required.

5.6.1.5 TSF 3D Groundwater Model

A modified version of the 3D basin-wide groundwater flow (in MODFLOW-SURFACT) was used to assess the potential for seepage from the TSF to downgradient surface water receptors.

For this purpose, the model domain was reduced in extent to exclude the steep topography west of the mine (Figure 5-9). This was done to facilitate model convergence. In addition, the tailings deposit was explicitly included in a new model layer. Furthermore, surface water features in the footprint of the TSF were removed and recharge estimates obtained from the 2D cross-sectional model were applied to the tailings beaches. The tailings pond was simulated with the MODFLOW-96 river package which permits flow between surface water features and groundwater based on a conductance assigned to the bottom of the surface water body.

Sensitivity analyses were completed using the 3D TSF model to bracket the potential range of seepage from the TSF and to estimate the relative proportion of TSF seepage reaching different surface water receptors.

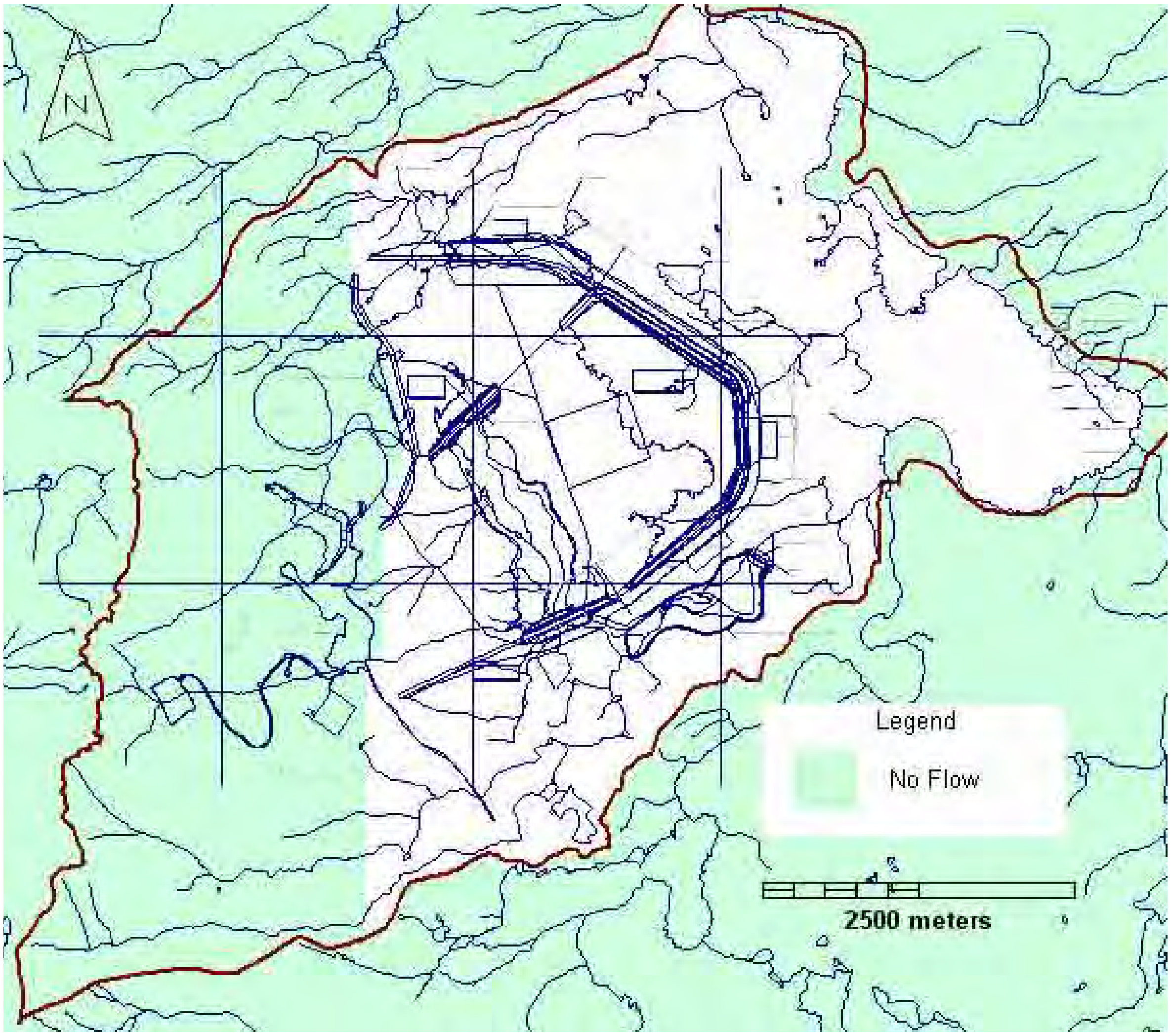


Figure 5-9: Model domain for 3D TSF Model (using MODFLOW-SURFACT), Case Study 1.

5.6.2 Case Study 2: Underground Mine

Case Study 2 illustrates the use of a 3D saturated flow model to study the potential environmental impacts of an underground development. A more detailed description of this case study is provided in Appendix C.

A basin-wide fully three-dimensional saturated flow model was used to assess

- Transient dewatering during adit construction
- Transient dewatering during mine operation
- Transient simulation of post-closure rebound, flow, and transport.

5.6.2.1 Groundwater Flow Model

The finite-difference code MODFLOW was used to simulate groundwater flow. Visual MODFLOW was used as the GUI.

A 3D numerical model was essential for simulating the complex groundwater flow and discharge associated with the underground mine workings and spatial distribution of hydrogeologic units.

Although continuum models, like MODFLOW, do not address discrete bedrock fractures, the modeller noted that the applicability of an equivalent porous media approach to simulations of flow and transport in heterogeneous, fractured bedrock settings has been well proven and documented. Beyond this, the rationale for adoption of an EPM approach for this specific site was not clearly expressed in the model documentation.

Initially, a detailed 3D model had been developed which included 40 layers bounded by surface watershed divides. However, this model was found to be too unwieldy and the vertical discretization was subsequently reduced from 40 layers to 17 layers without compromising the delineation of hydrostratigraphic zones. To represent the underground mine workings, simple drains replaced the more complicated inactive zone-drain combination used in the updated model.

The updated model was also expanded to the north and south to be able to simulate potential cross-boundary flow from the adjacent watersheds to the underground mine during mine dewatering (see Figure 5-10 for updated model domain and boundary conditions). Fourteen surface water features were included as constant head and general head boundary conditions (lakes and marshes, respectively).

The revised model significantly reduced the overall complexity (and run-time) of the numerical model, yet at the same time provided more reliable modelling results. This example illustrates that a judicious use of model discretization can significantly reduce cost and time without compromising the modelling objectives.

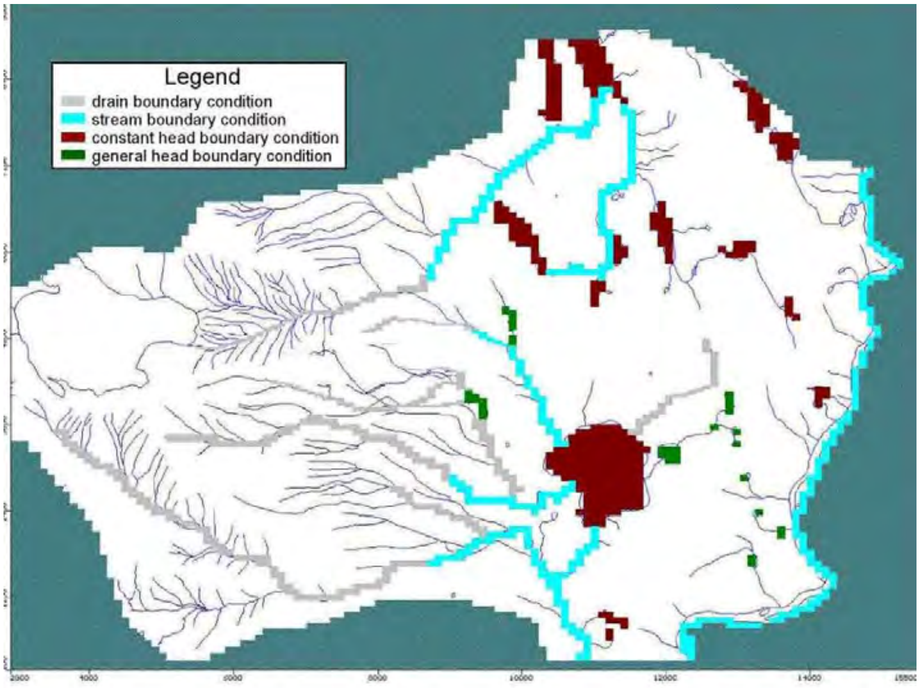


Figure 5-10: Model domain for 3D Basin-wide Model (using MODFLOW), Case Study 2.

5.6.2.2 Solute Transport Model

The particle tracking code MODPATH and the solute transport model MT3DMS were used to simulate contaminant transport for the post-closure conditions (after mine flooding). CoCs for this project included molybdenum and arsenic which were observed in elevated concentrations in mine water discharging from an existing adit.

First, particle tracking was used to estimate the advective path and travel time of a group of particles introduced to the system (Figure 5-11). Particles were assigned to the new adit, the underground stopes, and beneath the load-out facility. Particle tracking confirmed that mine CoCs may reach groundwater discharge points several decades after closure. The particle tracking exercise helped to identify potential receptors, but was not able to provide estimates of CoC concentrations (nor travel times for reactive contaminants).

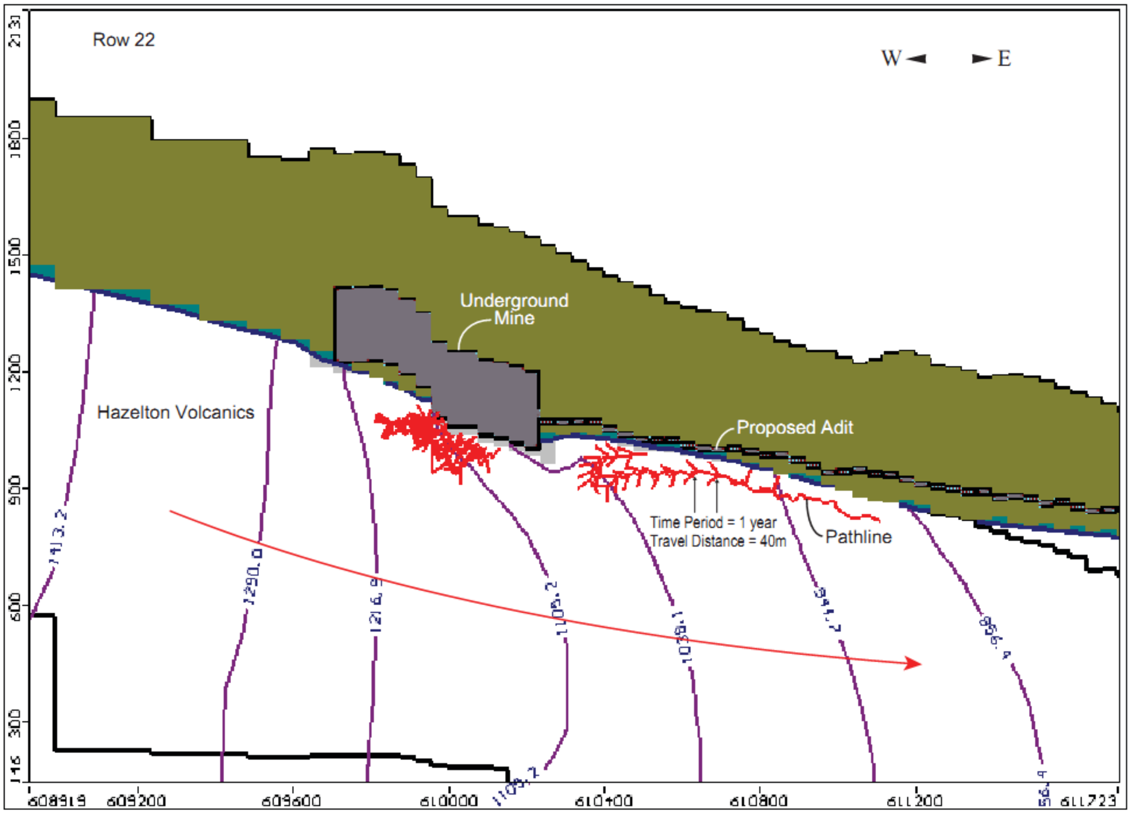


Figure 5-11: Pathline analysis using MODPATH, Case Study 2

Following the MODPATH simulations, the solute transport module, MT3DMS, was used to simulate transport of potential CoCs in mine water to the receiving environment. No specific solute was simulated in the transport model. Instead, an arbitrary concentration of 100% was applied to all granodiorite and mine cells. The model did not simulate adsorption/absorption to rock surfaces or degradation.

This example of solute transport modelling illustrates the recommended phased approach for contaminant transport modelling. First, particle tracking analysis was completed to determine whether the CoCs present in mine water could potentially reach VECs. Second, solute transport modeling was conducted to predict the timing and magnitude of CoC concentrations at various VECs (drinking water wells).

5.6.3 Case Study 3: Groundwater Extraction Project

Case Study 3 illustrates the use of a 3D saturated flow model to study the potential environmental impacts of a large groundwater extraction project. A more detailed description of this case study is provided in Appendix C.

An existing three-dimensional groundwater flow model was used as the basis for numerical modelling. The model domain was reduced and discretization was refined to focus on the Site's surface water and groundwater systems. The three-dimensional MODFLOW code was used to simulate steady-state and transient flow.

The model domain covers approximately 80 km^2 of a regionally extensive aquifer. The domain boundaries were defined by large surface water features and the US-Canada border, which lies at a considerable distance to the south of the wells being assessed and therefore would not influence the flow solution (Figure 5-12). Vertically, the model was discretized into 11 layers representing the hydrostratigraphic units identified in the conceptual model. Creeks and streams within the model domain that were interpreted to be perched above the aquifer were assigned river boundary conditions, while those interpreted to intersect the aquifer were assigned drain boundaries.

The groundwater flow model was calibrated against a spatially and temporally distributed set of observations, including transient calibration to a pumping test. Predictions included an estimate of the groundwater zone of influence due to increased withdrawal rates and estimates of baseflow impacts to potentially vulnerable creeks.

This case study is a good illustration of the level of detail required to evaluate potential impacts of a large groundwater resource project in a regional aquifer which is influenced by seasonal recharge and multiple users.

SUMMARY POINTS FOR MODEL SELECTION

1. The most important factors to consider in mathematical model selection are the modelling objectives and the conceptual model.
2. The modeller (or reviewer) should assess the groundwater flow field to determine the dimensionality of groundwater flow. The degree of heterogeneity (including the presence of preferential pathways) and the anticipated hydraulic stresses should also be considered in determining the dimensionality of the problem.
3. Any simplification of a three-dimensional flow problem should be justified. An estimation of the resulting error should be provided and the potential implications for model predictions should be discussed.
4. Any simplification of a transient flow problem to a steady-state problem should be justified. It should be demonstrated that this simplification yields conservative estimates of environmental impacts.
5. These guidelines generally recommend the use of the Equivalent Porous Medium (EPM) approach for groundwater modelling in fractured bedrock, but the application must be reasonably justified for the project site. Note, however, that the use of the EPM approach in moderately to sparsely fractured bedrock significantly increases model uncertainty. Greater uncertainty should be expected when modelling transport processes with an EPM approach, as the direction and timing of contaminant transport can be strongly influenced by flow through discrete fractures. If applied to fractured bedrock, the limitations of the EPM approach and potential implications for model predictions should be discussed in the model report.
6. The use of variably saturated flow for large-scale models of groundwater flow (e.g. at the basin scale) is uncommon and not recommended. If a variably-saturated flow solution is used to solve a 3D flow problem, this approach and the hydraulic parameters assumed for the unsaturated zone, should be justified and documented.
7. A phased approach should be adopted for modelling water quality impacts. Initially, particle tracking should be used to determine the potential flow paths and the risk to VECs. Preliminary (conservative) estimates of contaminant loads and/or contaminant concentrations to VECs should be obtained to assess whether applicable guidelines may be exceeded. If these conservative calculations indicate a potential risk to VECs, then solute transport modeling should be considered.
8. Conservative transport modelling should precede reactive transport modelling to identify whether the additional complexity of reactive transport modelling is justified.
9. For projects with relatively simple physical settings, or where the required accuracy of model predictions is not very high, analytical models may be adequate to simulate groundwater flow and/or contaminant transport. Analytical models may also be used to check that numerical solutions produce reasonable answers.
10. Numerical models should be considered where the scale and importance of the problem warrant the use of a more sophisticated approach. Numerical models should not be used as an alternative to data collection. Instead, appropriate use of a numerical model may require and/or help guide additional data collection so that the model can be properly parameterized and calibrated as well as support system interpretation.

6 NUMERICAL MODEL SETUP

Once a conceptual model has been developed (Section 4) and the most suitable modelling approach has been determined to be numerical methods, the numerical code must be selected (Section 5) and the conceptual model has to be implemented into a numerical model (see Figure 2-1). This step of the modelling process is often referred to as “model setup” but is also known as “model development” or “model construction”.

In essence, the numerical model setup represents the process of converting a qualitative conceptual model into a numerical model, i.e. a complex set of mathematical equations that can be solved numerically. In order to solve the numerical model the mathematical problem needs to be properly posed. This requires the definition of the following:

- Model domain and boundary conditions
- Model layers and discretization
- Boundary conditions, internal sinks and sources
- Model parameterization
- Initial conditions and time stepping in transient simulations
- Model convergence

In developing (or reviewing) the numerical model setup, the modeller (or reviewer) should ask whether and how the numerical model boundaries and property distributions adhere to the conceptual model, and whether the model setup could potentially bias the model predictions in a way that is not intended.

This section provides an overview of the technical aspects of model setup (listed above) and provides guidance on their use in groundwater models for the natural resource industry. Where applicable, potential problems that may arise during model setup and their implications for model predictions are also discussed.

It should be recognized that the construction of a numerical model requires a solid understanding of the mathematical assumptions underlying the numerical modelling code and the various aspects of model setup. Although important, a discussion of the mathematical aspects of numerical modelling is beyond the scope of these guidelines. For more details on the numerical methods the reader is referred to standard groundwater modelling textbooks (e.g. Anderson & Woessner, 1992).

A comprehensive check list of specific information that should be considered for the numerical model setup is provided in Appendix D.

6.1 MODEL DOMAIN AND EXTERNAL BOUNDARIES

The first step in model construction is the definition of a suitable model domain which should encompass the area for which groundwater flow (and potentially contaminant transport) is to be studied. The domain of the numerical model usually coincides with the domain of the conceptual model (but is sometimes smaller). The model domain encloses the geological volume of interest within which the mathematical simulation of groundwater flow and transport is computed.

The boundaries of the model domain are referred to as “external boundaries”. The effect of these boundaries on heads and flows must then be conceptualized, and the best or most appropriate mathematical representation of this effect is selected for use in the model (also referred to as “boundary condition”).

The delineation of the model domain is dependent on the selection of suitable external boundary conditions. It is generally preferable to use physical hydrological features which are known to control groundwater flow such as watershed divides, lakes, aquicludes etc. In some cases, the flow problem is simplified by defining a model domain which represents only a small portion of a larger, naturally bounded groundwater system (e.g. regional aquifer, basin, valley, island). When physical hydrologic features that can be used as boundary conditions are far from the area of interest, artificial boundaries are sometimes used. The external boundaries of the model domain must not be restrictive of the applied stress on the study site and must be compatible with modelling objectives (e.g. extent of dewatering or depressurization caused by mine pit excavation or pumping of wells). Therefore, whenever possible, the natural hydrogeological boundaries of the flow system and an appropriate model extent to capture the expected hydraulic stresses, should be used as the model domain boundaries of the numerical model (see section 6.3 for more details).

6.2 MODEL LAYERS & DISCRETIZATION

A fundamental aspect of numerical models is the representation of the hydrogeological system with discrete elementary volumes. This discretization within the model domain is either represented by an orthogonal grid of model cells (“finite-difference” method) or a mesh of 3D elements (“finite-element” method) (Section 5.3). The spatial resolution or spatial accuracy of the model is limited by the size of the discrete volumes. In some cases the ability to represent a flow or transport process is also limited by cell or element size. Other considerations are the size of discrete features to be represented (e.g. fault zones, tunnels, dam faces, pumping wells, narrow geologic units, cutoff-walls, streams and ditches, etc.). A secondary consideration in cell or element spacing is the variability in aquifer properties—which is usually not known with greater accuracy than the typical model cell or element size—but becomes important in representing structural faults or boundary conditions in large regional models with large cell or element sizes. These guidelines provide examples of finite-difference models (with MODFLOW examples) and finite-element models (with FEFLOW examples).

The finite-difference grid has an orthogonal pattern and the model grid should be oriented to enclose the area of interest while minimizing the number of inactive (unused) model cells. If there is significant and uniform anisotropy in hydraulic conductivity across the site it may be advantageous to orient the model grid in this direction. However, most modelling codes allow the use of anisotropy at an angle different to the model grid. The finite difference grid can be refined by increasing the number or rows and columns abruptly or gradually (telescopic refinement) to obtain the desired refinement near features of interest (Figure 6-1).

The use of finite-element meshes provides more flexibility and can be more efficiently refined in many locations within the model domain (Figure 6-2). The finite-element mesh does not need to be oriented, and the mesh can be shaped to efficiently enclose a model domain. There are no inactive nodes in a finite-element mesh because the elements are fit exactly to the boundary. Anisotropy can be specified independently of a mesh shape.

Most models have a much larger horizontal extent than vertical extent, although in some situations the vertical extent may be as large as the horizontal extent (e.g. mine workings in very steep topography, models of vertical mine shaft dewatering). In most cases, the models are arranged such that the grid or finite-element mesh is used for model discretization in the horizontal or nearly horizontal dimension. However, for cross-sectional problems, the orientation of the grid or mesh can also be applied to a vertical plane to allow better vertical resolution. (e.g. idealized slope section of specified length represented in section-view by a finite-element mesh). Finite-difference grids result in rectangular volume elements, but the grid refinement can be specified only in one plane similar to finite-element mesh refinement in one plane.

Model layers are used for discretization in a direction perpendicular to the grid or mesh, usually in the vertical direction. In this sense, the finite-difference model, such as MODFLOW, is the same as the majority of commonly used finite-element model codes, such as FEFLOW. Both model types allow the use of layers that can be of uniform or variable thicknesses.

6.2.1 Cell or Element Size and Horizontal Discretization

Selecting the size of the cells or elements is an important step in numerical model design. The intended use of the model and the importance and size of the features being discretized affect both the evaluation of whether the model is discretized appropriately and whether important features are missing that would cause a systematic error or bias in the simulation results. Hydraulic properties and stresses are specified for each cell or element. Therefore, finer discretization of a model domain allows for finer definition of hydraulic properties and more accurate solution of stresses. In the past, the grid and mesh sizes were severely limited by the computational power of computers, but modern computers allow the modeller to use a very fine grid or mesh discretization that is often finer than required to solve a problem correctly. However, certain types of models, such as unsaturated flow or transport models, may require finer grid or mesh discretization.

The goal of discretization is to achieve an adequate model and prove it with sensitivity analysis, not to maximize model discretization to the maximum computer power available. Beyond certain discretization, the model solution does not change significantly, yet may be smoother in appearance or the water balance might be slightly better, but at a cost of longer computing times. At a minimum, the model cell or element size should be small enough to represent all the features of interest (e.g. mine tunnels, ditches, pumping wells, streams, shafts, small ponds, waste rock piles, etc.) as well as their properties and boundaries or sources and sinks. The model cell or element size should also be small enough to simulate applied stresses adequately. At the same time, the modeller should avoid introducing unnecessary cell discretization as this may unnecessarily complicate the modelling process. A larger, more complex model will take longer to run and may introduce more potential for error. In many instances, a simpler, smaller, faster model is preferred as it allows for more model runs during sensitivity and uncertainty analysis for a given modelling budget.

It is good modelling practice to start with a relatively coarse model grid and then subsequently refine the model discretization until the modelling results are stable and meet the required accuracy. The final model discretization should be discussed and justified in the modelling report. For projects, in which modelling results are sensitive to model discretization (e.g. flow and transport in heterogeneous media, such as bedrock with discrete high-permeability faults), sensitivity analyses on model discretization (e.g.

doubling the grid or mesh refinement) should be conducted and discussed in the modelling report, with a focus on the results for the areas of increased grid refinement.

Local model refinement may also be required near important point sources or sinks such as pumping wells. The hydraulic head distribution is most complex near the well and the numerical solution is affected by the discretization of model cells. A finite-difference model does not simulate the hydraulic head gradient near a pumping well accurately, because the model extracts or injects water to the cell block volume which is usually much larger than the well diameter. The resulting head at the well is not a good approximation, but the heads away from the well are correct. If accuracy of the head near the well is not important to the problem, then the coarse grid is probably acceptable. But, if accuracy is needed near the well, then the finer grid would be necessary. Note that analytical equations are available to compute the drawdown in a pumping well simulated with a coarser grid. Finite-element models calculate the head in the pumping or injection well directly at the node, unless the well is placed between nodes. The hydraulic head is simulated more accurately at point sources, and sinks in finite-element codes.

Finite-difference models generally allow the widths of rows and columns to vary, which is called variable grid spacing. The use of variable grid spacing allows some flexibility to make cells smaller in some areas and coarser in other areas or to provide a smooth change of cell spacing). However, in some models there are advantages of using uniform, finely discretized grids, which provide the most accurate solution and simplify mapping of properties and boundaries. In finite-element models (e.g. FEFLOW), the mesh can be refined smoothly around points or lines or within specified areas, giving large flexibility in model design.

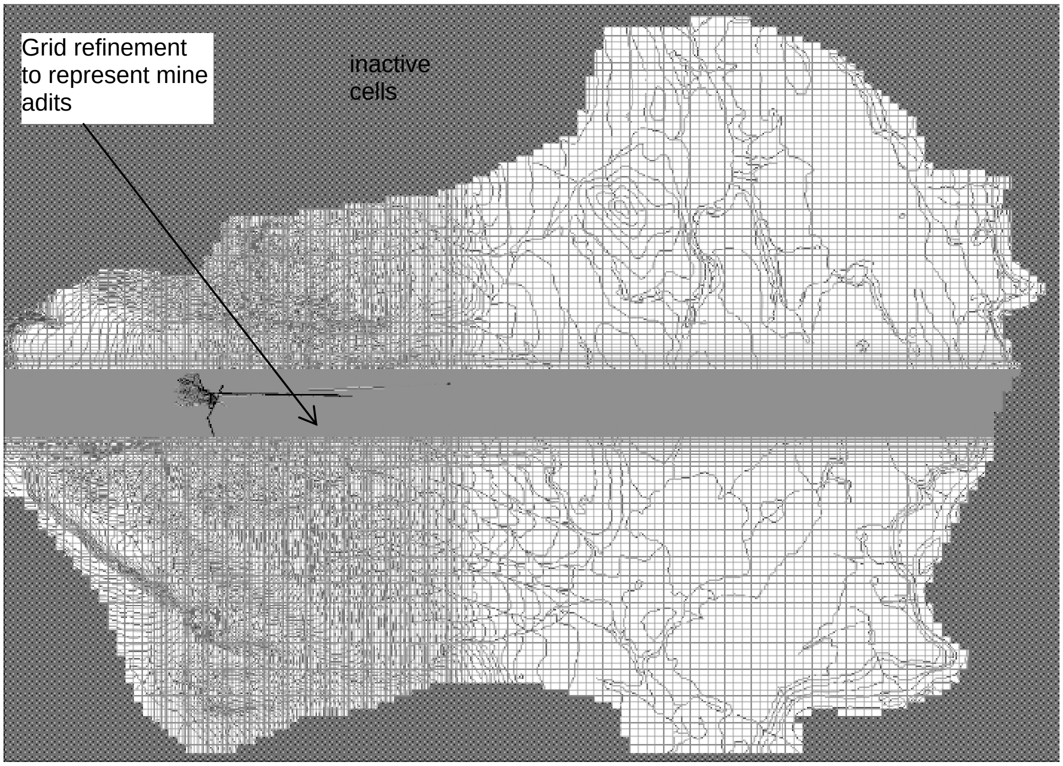


Figure 6-1: Examples of finite-difference grid discretization in MODFLOW Case Study 2.

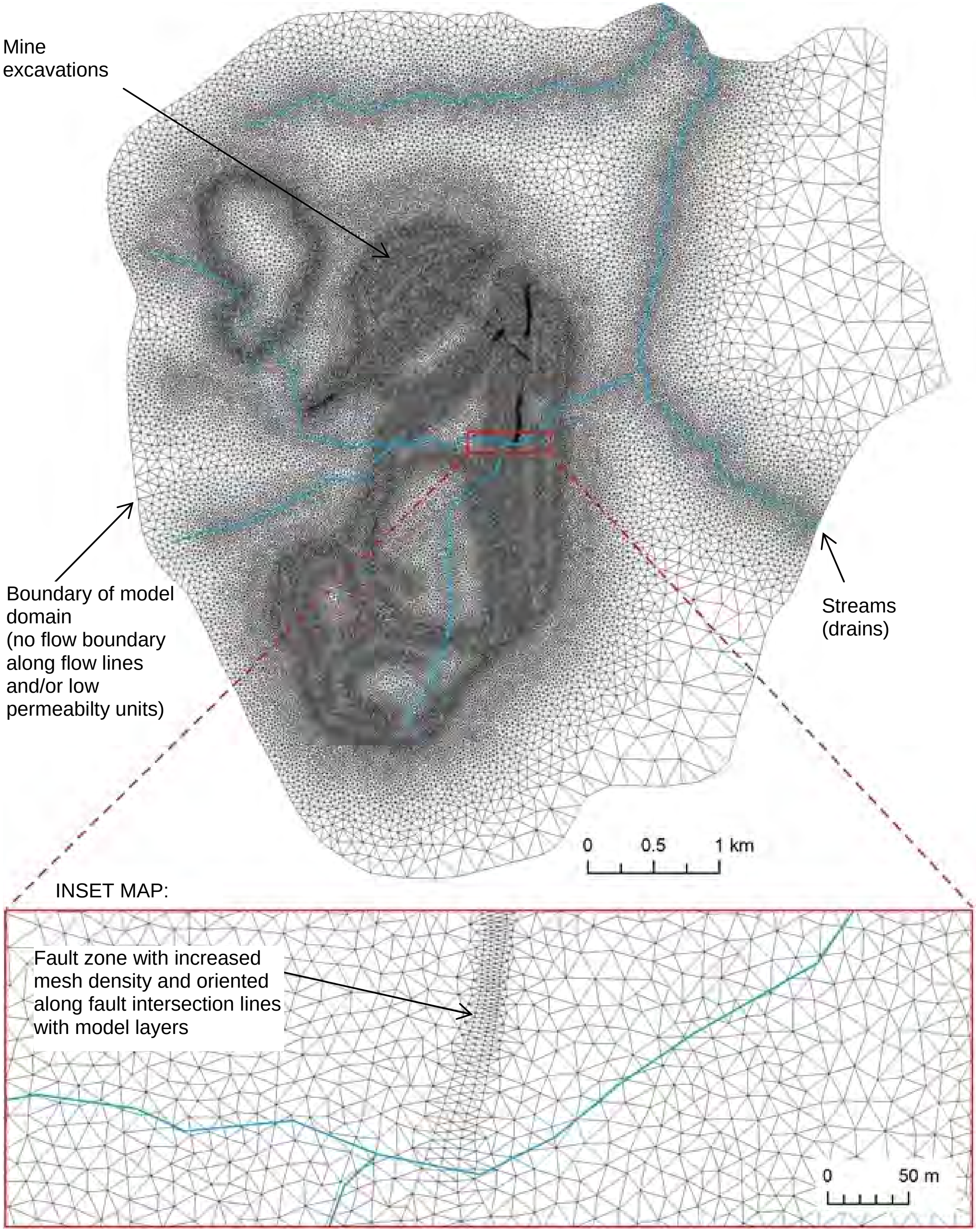


Figure 6-2: Examples finite-element mesh discretization in FEFLOW.

6.2.2 Vertical Discretization

Vertical discretization may be required in a groundwater flow model to explicitly represent variation in aquifer properties with depth (e.g. the presence of a confining layer separating two aquifer units) or simply to provide better resolution of vertical gradients (even in a relatively uniform system). The degree of vertical discretization will depend on the modelling objectives. For example, a simple two or three layer model may be adequate for a regional flow model where horizontal groundwater flow dominates. In contrast, a detailed vertical discretization may be required to simulate inflow to an open pit in a bedrock setting with significant vertical heterogeneity.

Again, it is good practice to start with a relatively simple vertical discretization that covers only the essential features of the conceptual model (e.g. different hydrostratigraphic units). Sensitivity analyses can then be conducted to determine whether additional vertical discretization is required to adequately simulate the vertical aspect of groundwater flow. In any event, the model documentation should justify the vertical discretization used in the model.

Two approaches are commonly used to represent the discretization of a conceptual model in the vertical dimension: (i) uniform model layers (a rectilinear grid) and (ii) deformed model layers (see Anderson and Woessner, (1992) for more details). The deformed layers have layer boundaries usually following the surfaces of hydrostratigraphic units. Deformed model layers allow horizontal continuity to be maintained with fewer cells at the expense of introducing some error in the finite-difference and finite-element solution. The uniform layer approach has the advantages of simplicity and a stable solution, but may require more vertical discretization to adequately describe the vertical extent (thickness) of hydrostratigraphic units. It is also possible to create deformed layers for most units and to use regular (uniform) layers to subdivide selected hydrostratigraphic units achieving locally-fine vertical discretization (see Figure 6-3 from Case Study 2).

The model grid or mesh may also be used in profiling two-dimensional and three-dimensional models that have a rotated coordinate system (e.g. direction of gravity) to very accurately represent a portion of a site in a cross-section view. The limitations of such profile models are the inability to model radial flow to sources and sinks as well as the assumption of no flow boundaries as flow lines. However, such models are particularly useful in modelling a small section of approximately uniform slope or an elongated feature of interest.

Most three dimensional models, both finite-difference and finite-element use continuous layers in the vertical to model hydrostratigraphic units. Therefore, the problems with layer discretization are the same in these models (e.g. MODFLOW and FEFLOW programs). The following numerical issues should be considered when determining the vertical discretization in a layered numerical model:

- In deformed model layers only the dominant hydrostratigraphic units can be represented, and sub-units and heterogeneity is mapped by varying the unit properties locally (by zones). Where the layer surfaces are very irregular, the solution could be more difficult but the effect on numerical error is quite small (McDonald and Harbaugh, 1988). It is preferred to minimize layer irregularity and to keep layers horizontal or close to horizontal near planned mine excavations, where other inner boundaries will be added to the model (e.g. mine pit seepage face, mine tunnels, etc.).

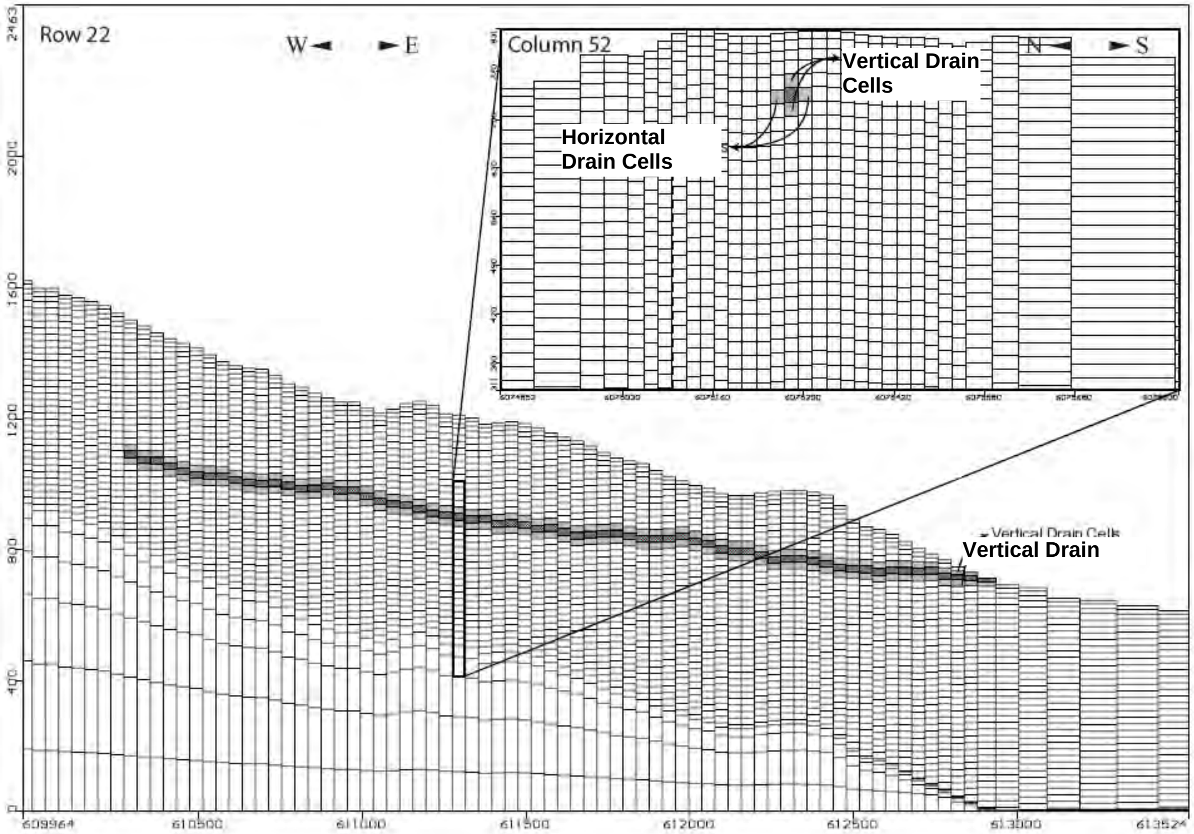


Figure 6-3: Example of highly discretized finite-difference MODFLOW grid layers in vertical dimension with drain cells to simulate mine adit (Case Study 2).

- Intermediate layers should be used to separate larger layers representing hydrostratigraphic units of highly differing hydraulic conductivity in FEFLOW. These buffer layers increase model accuracy and have properties equal to one of the adjacent units.
- Pinching out of aquifers or confining beds in three dimensional models can be handled by changing the transmissivity of the layer or the hydraulic conductivity of the confining unit. In most cases, the hydrostratigraphic units are very simplified and modeled as either continuous layers or discrete units.
- In uniform and finely spaced model layers (Figure 6-4), the hydrostratigraphic units can be mapped with hydraulic conductivity distributions at any scale from regional to local. Small, nearly discrete features (e.g. mine shafts, adits, drains, and pit fill materials) are easily mapped onto a regular grid in three dimensions with the use of appropriate CAD or GIS software.

For density-dependent flow models, the grid size should be smaller than in flow-only models to achieve the optimum solution accuracy. In density-dependent models the horizontal size of each grid cells should be 0.38% of the model domain length, and layer thickness should be ideally 0.60% of model domain (Al-Kaktoumi et al, 2007). The solution accuracy may be acceptable at coarser grids and meshes, but it should be verified by the modeller.

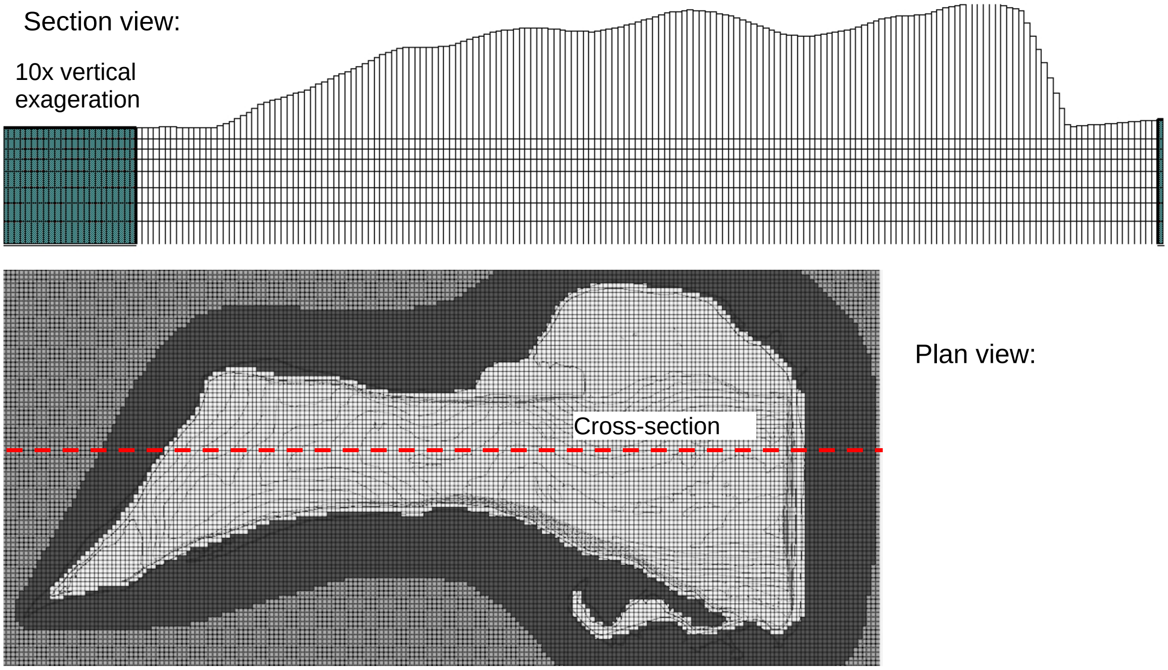


Figure 6-4: Example of regularly spaced horizontal layers shown in vertical cross-sections through 3D model

6.3 BOUNDARY CONDITIONS, SINKS AND SOURCES

When evaluating the appropriateness of a groundwater flow model, the boundary conditions are critical, because they determine where the water enters and leaves the system. If the boundary conditions are inappropriate, the model will be a poor representation of the actual groundwater flow system. The modelling objectives and the magnitude of the stresses to be simulated also influence the selection of the appropriate boundary conditions. When groundwater systems are heavily stressed, the physical features that control the system can change in response to the stress. For example, a flow line boundary (described in Section 6.3.2.) determined from current groundwater levels may be a plausible boundary for simulating current groundwater flow but is often not appropriate for model predictions of future stresses such as pit dewatering. Any representation of these features must account for these potential changes, either by understanding the limitations of the simulation or by representing the physical feature as realistically as possible.

Boundary conditions are mathematical expressions of the state of the physical system that constrain the equations of the mathematical model (ASTM, D5609.1220124). In solving a groundwater flow problem, however, the boundary conditions are not simply mathematical constraints; they generally represent the sources and/or sinks of water within the system. Furthermore, their selection is critical to the development of an accurate model. Not only is the location of the boundaries important, but also their numerical or mathematical representation within the model, because many physical features, which are often hydrologic boundaries, can be mathematically represented in more than one way.

The determination of an appropriate mathematical representation of a boundary condition is dependent upon the objectives of the study (see Section 4). However, if the model is intended to forecast the response of the system to additional withdrawals that may affect the stage of the surface-water bodies, then a constant head is not appropriate and a more complex boundary is required. A model of a particular area developed for one study with a particular set of objectives may not necessarily be appropriate for another study in the same area with different objectives. All of these boundary condition parameters must be considered in evaluating the strengths and weaknesses of a groundwater flow model (USGS, 2004).

Water and contaminants can flow into and out of the numerical model through:

- External boundaries of the model domain.
- Internal sources and sinks (internal boundaries) within the model domain.

The flow system is usually a mix of specified head and specified flow boundaries. The use of flux boundaries only, without any specified head boundaries, should be avoided due to the non-uniqueness of the solution. Steady state problems require at least one specified head boundary to reference the hydraulic head solution.

6.3.1 Types of Flow Model Boundary Conditions

The boundaries can be generally grouped into two conceptual types: physical boundaries and hydraulic boundaries. Physical boundaries do not change in response to groundwater flow or stresses in the groundwater system, or at least the change is insignificantly small. Hydraulic boundaries depend on the groundwater flow system and may change as a response to groundwater flow.

- "Physical boundaries" are formed by the presence of a "large" body of surface water (see Section 6.3.3 for details), by the presence of a very low permeability hydrogeological unit (e.g. rock unit, fault filled with clay gouge, ice, or permafrost zone), by an artificial barrier in a small scale model, or by a natural drainage network (e.g. site located on top of a mountain surrounded by deep valleys).
- "Hydraulic boundaries" (*artificial boundaries*) include groundwater divides and streamlines (flow lines) as well as *distant head boundaries* representing distant surface water bodies or arbitrary contours on a regional water table map. Hydraulic boundaries can be used to produce a steady-state flow field for calibration purposes, but these boundaries may not be acceptable for steady-state or transient predictive simulations of applied stresses. The use of a hydraulic boundary should be evaluated carefully to determine whether its use would cause unacceptable errors in the model.

All of the boundaries within the model domain, internal and external, can be represented with the same boundary conditions. There are many types of flow and transport model boundary conditions, where the hydraulic head, groundwater flux, or contaminant concentration is specified with some variations of constraints and interactions as well as variations in time and space.

6.3.2 No Flow Boundary (Streamline, Zero Flux)

A no-flow boundary does not allow any groundwater flow to occur across this boundary. In most numerical model programs, all the external surfaces and edges of the model domain are by default a no-flow boundary, if no other boundary type is specified. This means that the three-dimensional flow models do not "see" the ground surface and do not simulate any seepage of groundwater or runoff unless special boundaries are specified. The hydraulic head in any model node can rise or fall to any value, exceeding the vertical extent of the model if not constrained by boundaries. In most models, a no-flow boundary can also be specified anywhere in the model by using the specified flux boundary type (zero flux) or by using one of the hydraulic head boundaries with flux constraints specified as zero flux in or out of the boundary.

There are many common applications of no-flow boundaries:

- Groundwater divides are often chosen as no-flow boundaries, because they represent flow lines parallel to the boundary, so that there is no flow across the boundary. However, the locations of groundwater divides depend upon hydrological conditions and applied stresses, and can shift over time. Groundwater divides are dynamic boundaries and not physical boundaries of the flow system. Their representation as no-flow boundaries is justified only if the applied hydraulic stresses in the model domain have a negligible effect on the position of the boundary (e.g. the cone of depression of a water table or where depressurization does not reach the no-flow boundary during the applied stress such as mining excavations or pumping). See figure 6-5 for an example of where the stress reaches the boundary.

- Impermeable boundaries are natural geologic units or artificial materials which are regarded as effectively impermeable for modelling purposes, if the hydraulic conductivities of the adjacent materials differ by several orders of magnitude. In numerical models, a no-flow boundary can be represented with material properties, such as a very low hydraulic conductivity, without using hydraulic (head or flux) boundary conditions (head or flux). Mathematically, there is some flow in very low permeability materials and in models that do not allow zero permeability, but, effectively, such materials represent no-flow boundaries.

- In profile models of engineering structures, such as earth dams, the lateral boundaries are typically hydraulic streamlines, and the cross-section location in an elongated dam structure should be at least three times the depth of the structure. In other cases, the flow through the structure could be modeled in three dimensions.

- There are many complex engineering structures incorporating various cutoff walls, grout curtains, geomembranes and liners, frozen interiors, and other types. These structures could be considered as no-flow boundaries on a small scale, although most "impermeable" engineering materials are leaky to some extent and some may be very leaky. The choice of no-flow boundaries should be supported by engineering designs and field tests.

- The effect of density differences and transport of various fluids may in some cases affect hydraulic boundaries (e.g. a coastal aquifer saltwater interface or deep brine groundwater). For example, in a three dimensional flow model (freshwater flow only), the saltwater interface at the ocean shore is effectively a no-flow boundary with respect to water transfer because fresh and saline water does not mix easily in porous media. The use of a no-flow boundary assumes that there is no active salt water intrusion occurring. The sea water has tidal variation but if diurnal tides are not important for the project, the sea water body can be represented as a specified head of zero elevation along the shore line (see section 6.3.9. for details of specifying density-dependent boundaries).

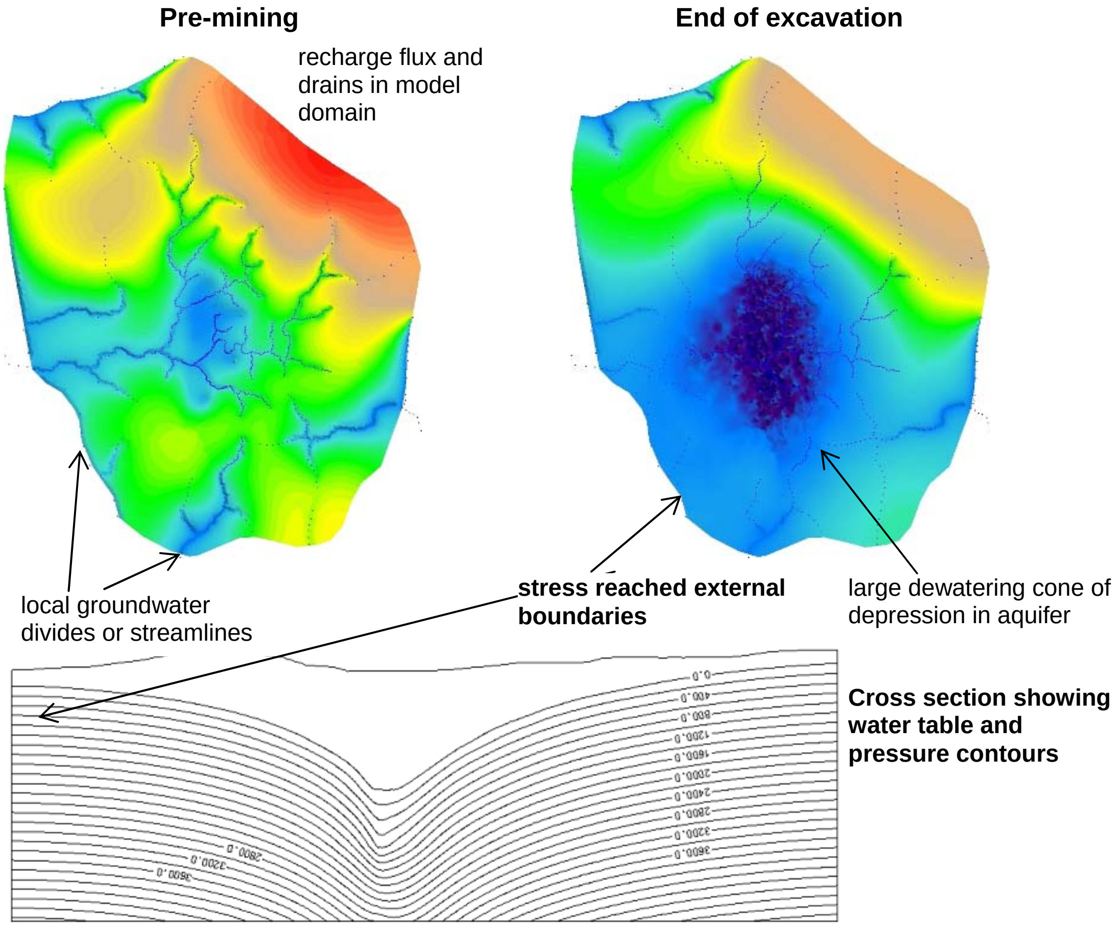


Figure 6-5: Example of eternal hydraulic "no flow" boundaries affected by mine dewatering stress on hydraulic head maps from model simulation results.

6.3.3 Specified Head Boundary (Type 1 or Dirichlet condition)

At this boundary condition the hydraulic head is specified as a function of position and time. There are several variations of this boundary type:

- *General specified-head boundary* represents a hydraulic head which may change with time and in space. It is often used as a boundary where the specified hydraulic head is far away from the actual model cells or nodes where this condition exists. For example, these boundary conditions can be used to create a hydraulic gradient to a distant hydraulic head boundary (e.g. a distant aquifer boundary or distant surface water body) that is either constant or varies independently of the groundwater system (e.g. tidal fluctuations or river stages). This boundary allows use of a smaller model domain in a larger regional setting, while simulating hydraulic gradients appropriately between the local site being modeled and distant aquifer boundaries, which are located in or beyond the model domain. In most cases the specified head boundary is fixed in space at the boundary location, but it changes in time in transient models (e.g. mine pit excavation schedule, pit lake draining, or filling schedule).

- *Constant-head boundary* represents a hydraulic head which does not change with time and is not affected by the simulated groundwater system. It is often used to represent large surface water bodies which are not affected by stresses applied to the groundwater system in the model (e.g. large lakes or rivers, large streams in some cases, or the sea). Another use is to represent the observed hydraulic head (e.g. water table elevation) along a groundwater divide or even an arbitrary boundary sufficiently far away from the modeled site.

6.3.4 Specified Flux Boundary (Type 2 or Neumann conditions)

In this boundary condition the groundwater flux is specified across the boundary (node, line, surface) as a function of position and time. There are several variations of this boundary type (Figure 6-6):

- *Constant flux boundary* represents the simplest type of specified-flux boundary, where the flux across a given part of the boundary surface is uniform in space and constant with time. Practical applications in models vary, but it is commonly used to model known point or line source recharge (e.g. a leaking water management system component such as pipe or ditch) or discharge (e.g. the measured outflow from mine workings or boreholes).
- *Specified flux boundary* can be variable in time and is commonly used to represent a known time-variable point or line source recharges or discharges (e.g. a variable leakage from water management structures or injection/ or extraction rates from point sources, etc.). In 2D models, this boundary type is often used to specify the groundwater recharge flux into the top of the model (net precipitation). It is also possible to specify aerial recharge with a flux boundary, but this is an inefficient use of model boundaries (reduces options).
- *General flux boundary* represents a groundwater flux rate that is variable in space and time. This boundary condition is not commonly used or available.

6.3.5 Head Dependent Flux (Type 3, Cauchy or mixed boundary conditions)

A head dependent flux is a boundary type where a flux across this boundary surface adjusts in response to changes in the hydraulic head adjacent to the boundary. The flux is a specified function of the hydraulic head and varies during the problem solution just as the head varies. There are several types of hydraulic head-dependent flux boundaries:

- A very common use for this type of boundary is to simulate flow to and from rivers and drains (Figure 6-7). A separate river and drain boundary is available in some modelling programs (e.g. MODFLOW) to specifically represent groundwater and surface water interactions. The drain boundary behaves similarly to a seepage face boundary. In some modelling programs, this boundary is represented by a specified flux boundary with hydraulic head constraints (e.g. FEFLOW).
- This boundary may be used to represent flux through a *leaky confining unit* which is not explicitly represented in the model with material properties.
- Evapotranspiration is another example of a head dependent boundary. It is a flux from the water table which is often modeled as decreasing linearly with depth to water and becomes zero where the water table reaches some specified “extinction” depth. In most modelling programs, the evapotranspiration is implemented separately or as an option in the aerial flux recharge.

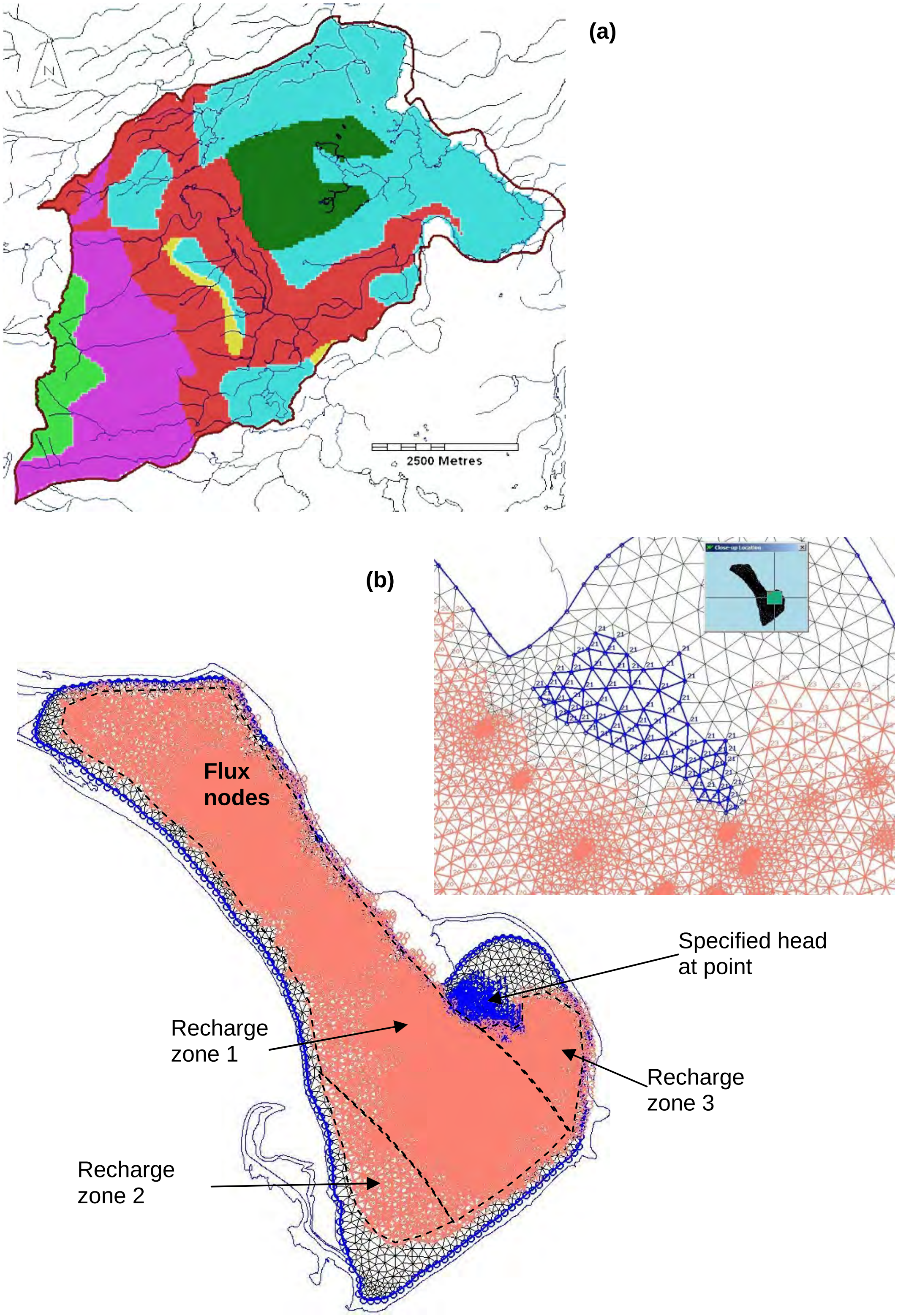


Figure 6-6: Examples of boundary conditions and internals sinks and sources involving specified flux: (a) recharge boundary zones in MODFLOW, (b) recharge flux and specified head boundaries in FEFLOW.

6.3.6 Seepage-face Boundary

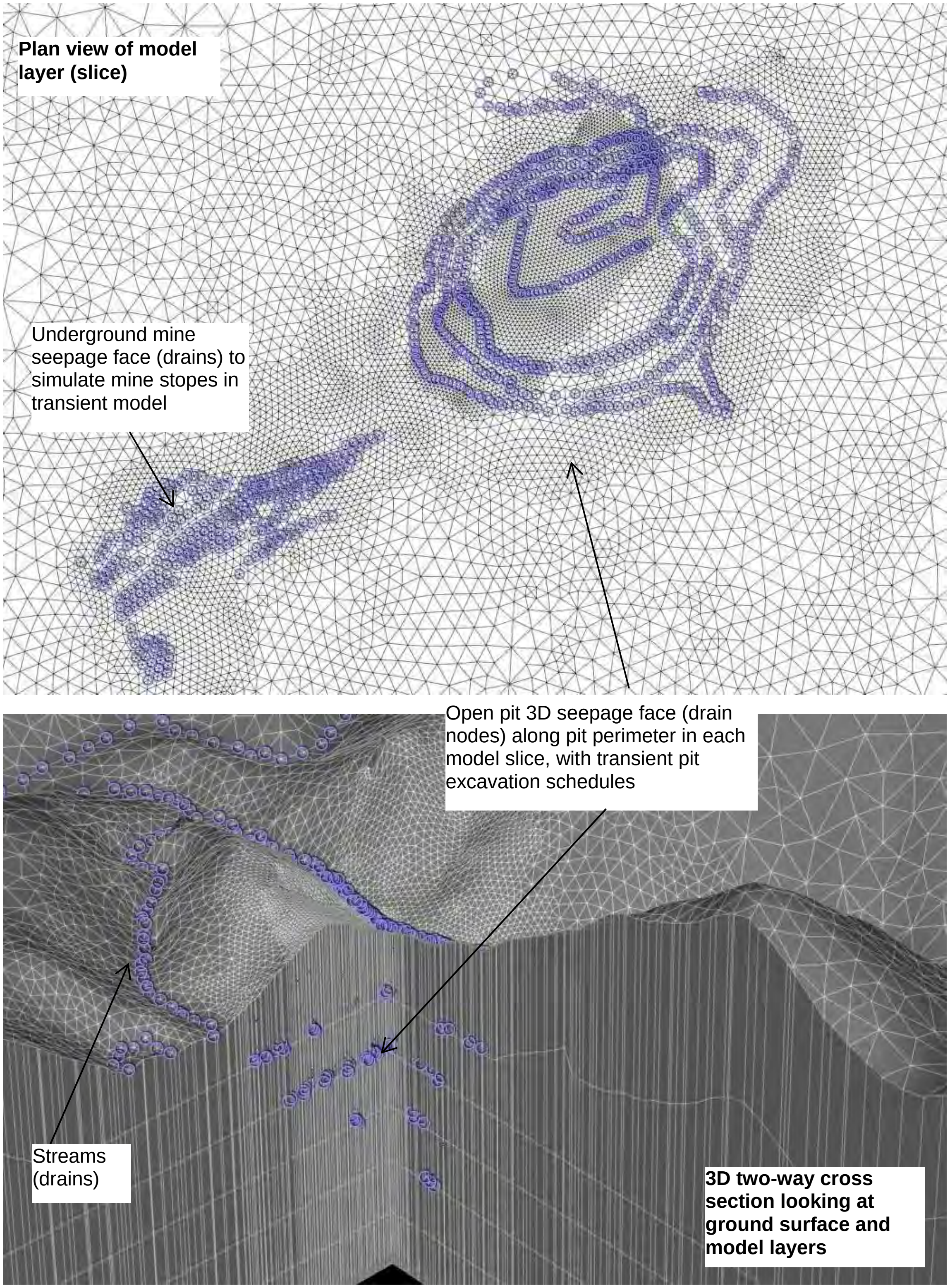
A seepage face boundary is a mixed boundary condition (head-dependent flux) which is very often used in the resource industry's groundwater models. A surface of seepage is a boundary between the saturated flow field and the atmosphere, either by flux into the boundary from the model domain or by evaporation. A seepage face can only extract water from the model domain but cannot produce water into the model domain (one way flux). The seepage of groundwater occurs from the saturated portion of the model and the water table always intercepts the seepage face. The location of this type of boundary is specified, but the boundary may become active or inactive and change properties over time in some transient models (e.g. mine pit progressive excavation). The applications of this boundary type are for all slopes where groundwater discharge may occur (e.g. mine pits and tunnels, ditches, natural drain channels, dam slopes, waste rock pile slopes, ground slopes) – see Figure 6-7.

- In some modelling programs (e.g. FEFLOW), the seepage face boundary is a type of specified head-boundary with a constraint on boundary flux direction to the boundary (flow is only allowed toward the boundary). In other modelling programs, this boundary may be implemented as a separate boundary type. This type of boundary is used to simulate seepage from surfaces, linear features such as drain channels or tunnels, or points (e.g. drilled slope drains with screens or pumping wells with unspecified pumping rate).
- Other modelling programs may have a separate boundary type named *Seepage Face Boundary*, separate from all other boundary types (e.g. slope stability engineering models or some analytical 2D models) or the GUI may offer a separate boundary type that is internally solved using a combined head and constrained flux boundary.

6.3.7 Pumping Well (or Injection Well)

A pumping well is an internal source or sink and a mixed internal boundary type. Most three-dimensional modelling programs have this boundary type, and the use is exclusively for simulating pumping or injection wells and boreholes.

- This source/sink allows variable fluxes in time to be specified, often with hydraulic head constraints to turn off the flux if the head falls below a specified elevation. Well screens, well skin effects, and other options may be specified. Pumping wells use specified flow rates to extract (or inject) water, depending on the hydraulic head conditions. Pumping wells are used in three-dimensional or axisymmetric models to simulate radial flow toward the well.
- Two dimensional profile models cannot simulate radial flow and conventional pumping well source/sink “boundary types”. Flux boundaries or drain nodes must be used, but the flow rates are not equivalent to real pumping rates calculated using three-dimensional or axisymmetric models.
- In some case it may be preferable to use a drain or a seepage face internal boundary at a point or line to simulate pumping or injection wells if the pumping rate is not known or is not important to the model solution. A seepage face or drain node allows the estimation of the maximum pumping rate possible at any point in time (e.g. for estimation of dewatering well requirements). This type of boundary allows for much faster transient model simulations because well drying and associated changes in time-stepping of the model are avoided.



Plan view of model layer (slice)

Underground mine seepage face (drains) to simulate mine stopes in transient model

Open pit 3D seepage face (drain nodes) along pit perimeter in each model slice, with transient pit excavation schedules

Streams (drains)

3D two-way cross section looking at ground surface and model layers

Figure 6-7: Examples of mixed boundary type (specified head + flux constraints) to simulate an open mine pit seepage face and surface stream drains in a 3D transient flow model using FEFLOW.

6.3.8 Free-surface Boundary ("Water Table")

A free surface boundary is a moveable boundary where the hydraulic head is equal to the elevation of the boundary.

- The most common free-surface boundary is the water table. Some modelling programs allow the deformation of the model domain during model execution. Deformable free surfaces may increase model efficiency, but should be treated with caution in complex models to avoid unexpected effects and changes in model layers.
- Another example of a free surface boundary is the transition between freshwater and underlying seawater in a coastal aquifer. If diffusion and transient changes are not significant to the model objectives, the freshwater-saltwater transition zone can be treated as a sharp interface and a no-flow boundary of the fresh groundwater flow system.

6.3.9 Density-dependent Flow Boundaries

In numerical simulations where the water density varies in space and has a significant effect on groundwater flow, a density-dependent model must be used (e.g. FEFLOW, SEAWAT, SUTRA). The applications are in modelling of saltwater intrusion, waste injection into saline aquifers, heat storage in aquifers, brine disposal, geothermal flow, etc. (Anderson and Woessner, 1992). It is not common to see density-dependent flow models in resource extraction projects, but some coastal areas might experience salt water intrusion during excavation dewatering or pumping of aquifers, or there might be deep brines involved in the groundwater flow system at some locations (mostly in northern Canada and not likely in BC). The fresh water-saline water interface is used as an example in this section.

The geometry of the freshwater-saline interface must be estimated from observations, analytical solutions, or other numerical density-dependent flow model results. It is a type of a hydraulic boundary that may not affect short-duration transient models if the stresses do not reach the boundary (it then can be treated as no flow boundary). In long duration transient models, however, the fresh water-saline water boundary may also change with time. In some cases, the model can simulate the formation or dissipation of a freshwater "lens" or zone above the saline water. Saline water may also be discharged into fresh water and then sink down due to density differences. The modelling objectives determine how these boundaries are specified.

The hydraulic head boundaries must be expressed as equivalent freshwater head values. The head nodes along the sea shore, for example, are assigned zero head values (or some exact mean sea level or transient sea level schedule). In three dimensions, or in two dimensional profile models, the equivalent freshwater hydraulic head varies with depth below sea level (or some reference elevation) as a product of density ratio between fresh and saline water and depth. This means that at appropriate model layers or slices or nodes, the specified head boundary values vary with depth (see example of an axisymmetric model with this boundary type in Figure 6-8).

Note that, as with transport modelling (see Section 9), there are additional parameters required to simulate density-dependent flow: representative mass for each water type (represented with chloride concentration or other), diffusivity and dispersivity, both of which are generally low. The reference mass is assigned for the concentration of a reference parameter (e.g. chloride) in fresh water originating from freshwater recharge flux source. The recharge flux boundary requires a constant "freshwater" concentration boundary to be specified as source of freshwater.

Corresponding to the specified head boundary of the fresh water-saline water interface is a constant concentration boundary with mass flux constraints to allow any types of water to exit the model (seep to shores) in the top model layer or slice, but allows the saline water flux to enter in other model layers or slices (saline water intrusion). For more details on density-dependent flow modelling the reader is referred to Anderson and Woessner, 1992; USGS, 2002, WASY, 2007).

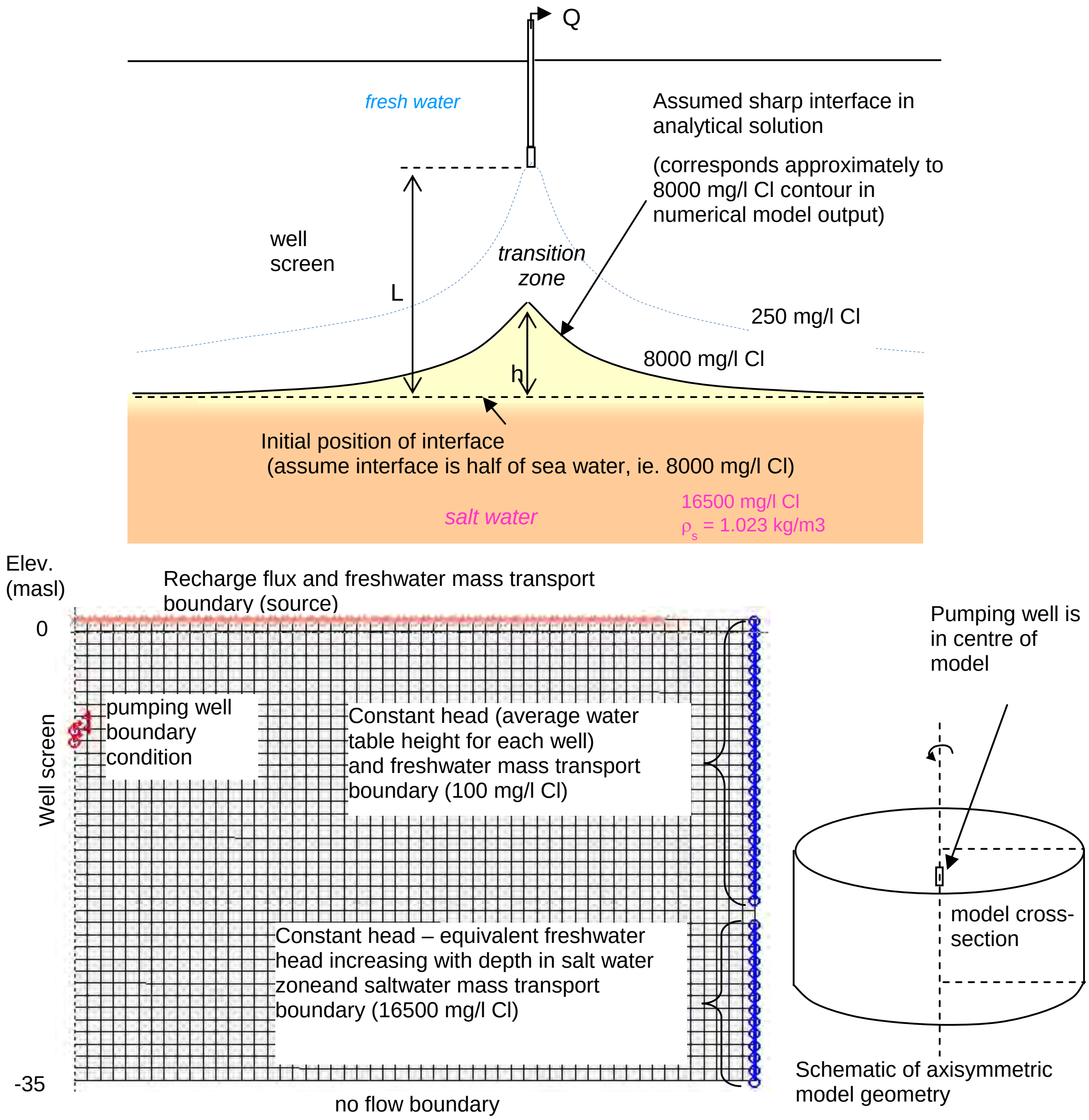


Figure 6-8: Examples of boundary conditions in axisymmetric model (2D cross-section) in density-dependent flow model.

6.3.10 Uncertainties of Boundary Conditions

The choice and setting of boundary conditions is a critical step in model design. Errors in boundary conditions may cause serious errors in model predictions. The uncertainty associated with boundary conditions can be described in four broad terms:

- Conceptual model representation of boundaries, sources, and sinks
- Implementation of boundaries in a numerical model
- Numerical solution (e.g. a water table)
- Stress dependency of boundaries (see next section)

Conceptual model representation

The physical or hydraulic boundaries must be represented appropriately and agree with the conceptual model in order to achieve good model results (see Section 4). The boundaries must be explained by the real hydrogeological system and supported by some observations (e.g. water levels) or by reasonable inferences based on physical process understanding (e.g. catchment drainage network and ground topography vs. groundwater divides). The known properties of geologic materials or artificial materials (e.g. waste rock dumps) should be reviewed in the conceptual model part of the modelling process, and the boundary conditions must take the whole hydrogeological system into consideration, including surface water and any planned future changes to the surface water drainage pattern.

Boundary condition implementation

Once the appropriate types of model boundaries, sources, and sinks are selected, these boundaries must be appropriately implemented or coded in the modelling model to achieve the intended behaviour as specified in the conceptual model. Common errors include:

- Data entry errors (e.g. errors in head or flux values or errors in the direction of flux)
- Wrong assumptions are used that are not supported by the conceptual model (e.g. specified head node or cell is an unlimited source of water)
- Oversimplification of boundary geometries relative to model objectives
- Too excessive complexity in boundaries that is not supported by observations (e.g. complex distributions of recharge fluxes to achieve better calibration of the heads)

The modelling program must correctly solve the flow and transport simulation and must properly use the boundary conditions. Numerical instabilities and lack of convergence may still occur in some cases in localized areas of the model domain, even after model convergence of the specified criteria for head and flux. In rare cases, the modelling files or the GUI may be corrupted and unintended behaviour of boundary conditions observed (or missed). Modern modelling GUIs present the hydrogeologist with many options and settings, which should be understood before using, and/or investigated numerically in a sensitivity analysis. The numerical behaviour of boundary conditions must be evaluated in terms of reasonable and expected behaviour at all steps in the numerical simulation process by the modeller.

Groundwater recharge is a very uncertain flux boundary. Typically, there is little data for total recharge at a site, much less for spatial distribution of recharge. However, recharge rates and zonation is usually defined through model calibration to observed heads, given some known aquifer properties. The uncertainty of aquifer properties will directly affect the uncertainty of the “calibrated” recharge flux, and the model solution is usually non-unique. For example, in a steady-state model, any combination of recharge and hydraulic conductivity can result in an identical head solution if the ratio of recharge to hydraulic conductivity (R/K) is the same. The difference between different combinations will be observed only in the model water balance.

Numerical solution of a water table boundary

The water table is a special boundary which is almost always solved numerically and not pre-specified. The models may use unsaturated/saturated conditions and represent the water table boundary as the surface of the zero pressure head. However, unsaturated parameters are difficult to estimate and the numerical solution has many complexities and is numerically demanding. Many three-dimensional models (e.g. MODFLOW) use Dupuit assumptions to approximate flow in the top (unconfined) model layer.

6.3.11 Stress Dependent Problems

The model boundary conditions must be examined if the model objectives include modelling of applied stresses to the groundwater system. The model representation of a system boundary may be a function of the nature and magnitude of stress applied to the system during model simulation. If the boundary conditions are stress dependent, the model cannot be considered a general, all-purpose tool for investigating any stress on the system, because it will give valid results only when the stresses do not impact the boundary. The study of a new stress on the same model may require the reformulation of the representation of model boundaries and sensitivity tests on the model boundary representation.

Stress-dependency is a primary concern wherever the model boundaries differ from the natural (physical) system boundaries. For example, the modeller may extend the model boundaries beyond the groundwater divide (i.e. a natural boundary) to simulate drawdown due to long-term pumping. Stress dependency of external boundaries of a model domain is usually evaluated with a larger model (larger domain extent) before a detailed local model is constructed. Each internal boundary can also be checked through a sensitivity analysis (adding, removing, or changing of boundary conditions and observing effects on the model simulation from the applied stresses).

Much of the sensitivity analysis to boundary effects in the model is done by the modeller during model development and calibration, and most of the problems are corrected without documentation in the modelling report. In cases where boundary interactions are observed in the predictive results, or if the model results are unexpected, a full sensitivity analysis should be presented on the boundary effects.

Boundary conditions strongly influence modelling results and the modeller (and reviewer) should critically evaluate the potential for errors in defining boundary conditions. The following examples demonstrate common errors:

No-flow boundaries affect stress calculation:

- No flow boundaries along the model’s edge may also cause mounding of recharge to levels above the ground surface in unconfined aquifer layers of the saturated flow model (see Figure 6-9a).
- No-flow boundaries of the model domain affect the model’s response to applied stresses at the site of interest. A hydraulic no-flow boundary is usually positioned far enough from the area of interest that whatever hydraulic stresses are simulated in the area of interest will not reach the distant hydrological boundary. A significant change in the hydraulic head near the no-flow

boundary suggests that the stress has reached the boundary and the solution is beginning to be affected by the boundary presence. Hydraulic head contours of a cone of depression caused by dewatering will be “bent” by the no-flow boundary on the head contour maps. An example of a drawdown caused by dewatering near an excavation and the effect of no-flow boundaries is shown in Figure 6-9b). In most models, the no flow boundaries are external boundaries only, therefore, the effect of no-flow boundaries, if present, will depend on the aquifer properties, distance to the area of interest where a stress is applied, magnitude and duration of applied stress, and other factors.

Specified head boundaries produce too much water:

- A more serious problem may arise from inappropriate use of specified head boundaries because the model may gain an unintended large flux of water from unconstrained specified head boundaries. A single inappropriately placed and unconstrained head node in the model can unintentionally (and erroneously) produce large quantities of water and completely change the water balance of the model solution. In this situation, the specified head boundary will artificially constrain the flow system by providing or accepting fluxes as a result of the nearby applied stresses.
- A classic example would be a small stream or pond which produces a large quantity of water into the model, much larger than is possible from its small observed stream flow or pond water balance. It is difficult to detect these errors during initial model review, but the water balance of the flow system should be examined for groundwater sources and sinks and any unusually large fluxes (see Figure 6-9c).

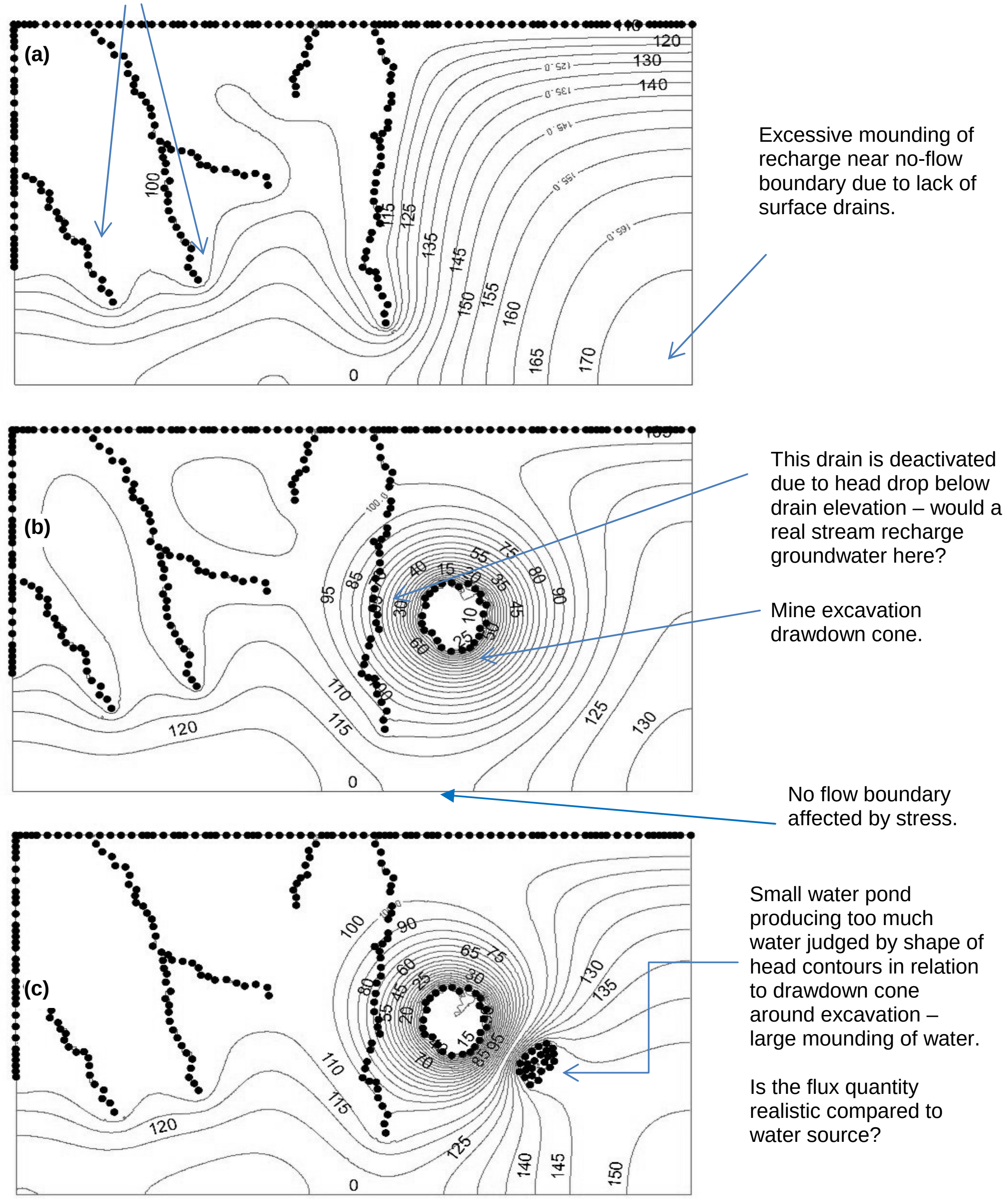
Specified head boundaries show unrealistic behavior during some stresses:

- A specified head boundary may function appropriately in natural conditions, but have unrealistic behavior under stress conditions. For example, a small to medium-sized stream, may function as a specified head boundary if the stress does not induce flow to or from the stream of sufficient magnitude to significantly affect the stream stage. If, however, the stress is so large as to cause a part of the stream to dry up, then the stream can no longer be treated as a specified head boundary. The stream may need to be modeled as a flux-dependent head boundary.

Specified flux boundary lacks head-dependency constraints:

- Specified flux boundaries without hydraulic head dependency assume the flux to or from the model is independent of the stress in the model. For example, applied recharge flux will not normally stop the flux when the water table rises to the ground surface leading to artificial mounding of the head above the ground surface (i.e. flooding) of the model. This behavior may not be noticed if there are many nearby drains which accept the recharged water, but the water balance of the model will be affected and may be in error. In particular situations, a head-dependent flux may be more locally appropriate in sensitive model areas.
- Spatially distributed recharge fluxes should be justified based on observations, soil properties, surface water hydrology, and climate. Highly variable recharge fluxes over the site of interest, specified to help model calibration, should be questioned. Any model can be calibrated to the head conditions using variable recharge distribution, but such recharge variability must be physically justified.

In summary, the model boundary conditions must be examined if the model objectives include modelling of applied stresses to the groundwater system, especially when hydraulic or artificial boundaries are used. Great care must be taken in implementation of boundary conditions in numerical models and the model results, including water balance, must be examined.



Excessive mounding of recharge near no-flow boundary due to lack of surface drains.

This drain is deactivated due to head drop below drain elevation – would a real stream recharge groundwater here?

Mine excavation drawdown cone.

No flow boundary affected by stress.

Small water pond producing too much water judged by shape of head contours in relation to drawdown cone around excavation – large mounding of water.

Is the flux quantity realistic compared to water source?

Figure 6-9: Examples of potential problems with specified head boundaries in a homogeneous aquifer.

6.4 MODEL PARAMETERIZATION

6.4.1 Concepts

An important aspect of representing the hydrogeological conceptual model is the choice of the hydraulic properties assigned to the model domain. In the saturated flow model, the properties include hydraulic conductivity and or transmissivity, unconfined and confined aquifer storage properties (specific yield and specific storage), and aquifer compressibility. In the unsaturated flow models, there are more properties specifying the function of hydraulic conductivity with saturation (i.e., soil water characteristic curves). Transport models will require additional properties to describe the interaction of contaminants with porous media (see Section 9).

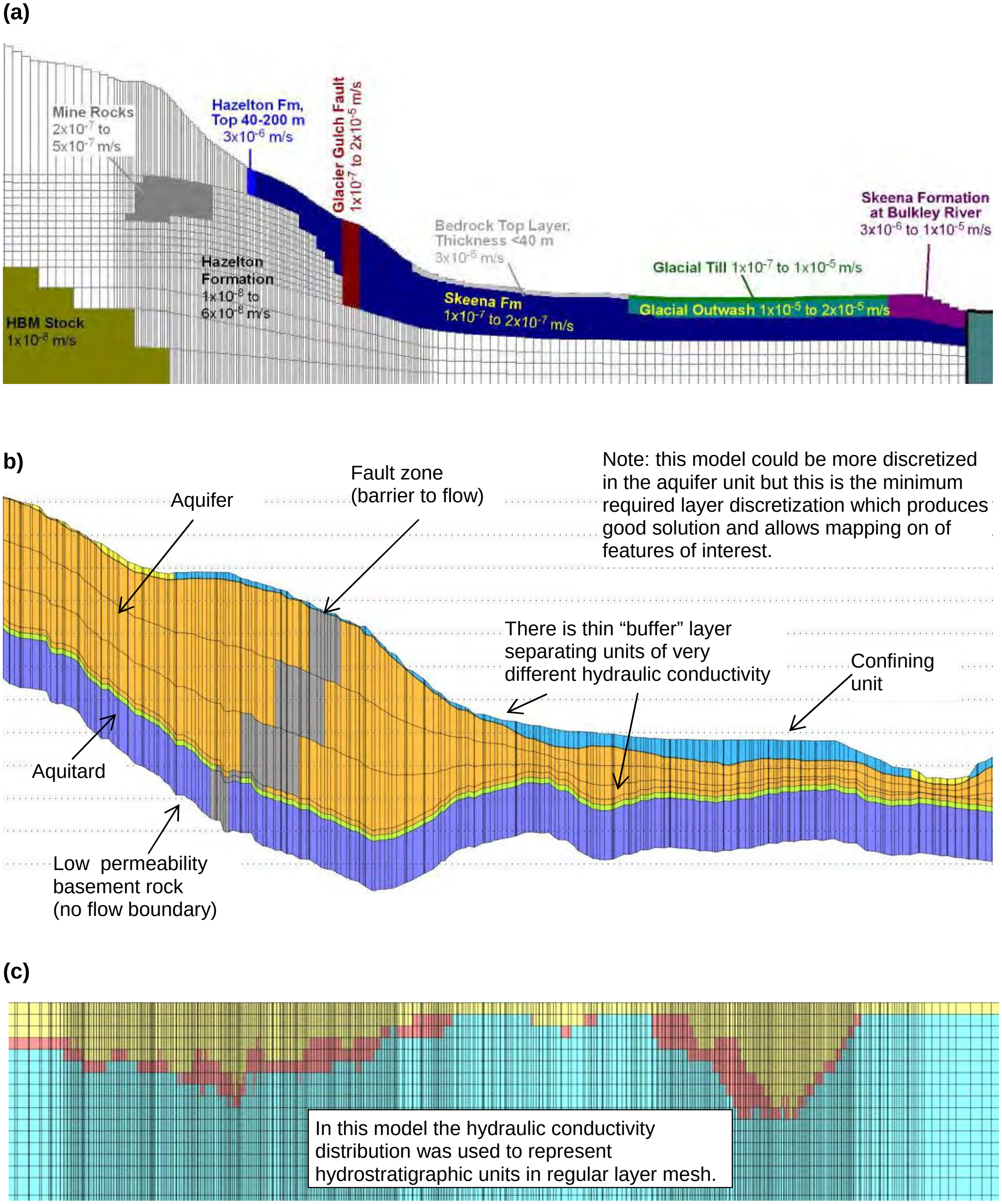
In every numerical flow model, the properties are assigned to model cells or elements and are usually assigned to layers of cells or elements. Each model cell or element can have different properties. Given the uncertainty of knowledge of the distribution of hydraulic properties from available data, the modeller must choose the most appropriate representation of these properties. The following types of spatial distributions of properties are commonly used in flow models:

- *Uniform distribution* is based on a single representative value of a parameter in a large unit or in many discrete sub-units each with uniform distribution, (i.e., one value).
- *Interpolated (spatially variable) distribution* is based on an assumed or observed variation of the parameter in space.
- *Anisotropy*, specified for hydraulic conductivity, is based on geological information and sometimes on hydraulic testing results. It is often used to deform the flow field to help with model calibration.

6.4.2 Uniform Distributions

The mean value of hydraulic testing results is usually used to represent one homogeneous hydrostratigraphic unit or each sub-unit within a larger unit (Figure 6-10). The method of averaging hydraulic conductivities is not a simple choice, and it depends on the type of statistical distribution of data, flow direction (e.g. vertical across many hydrogeological units or horizontal within one hydrogeological unit), and the nature of heterogeneity of porous media (or equivalent porous media for fractured bedrock). There are three commonly used averaging methods to produce a mean value, which increases in value in this sequence: arithmetic mean, geometric mean, and harmonic mean. In most models, the hydraulic conductivity is adjusted during model calibration, but the field test data usually provides reasonable bounds for this parameter.

Most hydrogeological studies and modelling results support the use of the geometric mean of K, for bedrock aquifers assuming a good site-wide connectivity of fractures, although some hydrogeologists prefer the harmonic mean for fractured rocks in a poorly connected fracture network. The geometric mean is used where the hydraulic conductivity distribution is log-normal (or normal), and the distribution is spatially random (i.e. hydraulic tests are independent). The harmonic mean is used to average the hydraulic conductivity values for flow that is perpendicular to different hydrostratigraphic units (e.g. flow across a low permeability fault or vertical recharge across a confining unit). Overall, the choice of the representative value or a mean value of model parameters has a large influence on model results and predictions and should be reviewed carefully.



Note: this model could be more discretized in the aquifer unit but this is the minimum required layer discretization which produces good solution and allows mapping on of features of interest.

There is thin “buffer” layer separating units of very different hydraulic conductivity

In this model the hydraulic conductivity distribution was used to represent hydrostratigraphic units in regular layer mesh.

Figure 6-10: Example of vertical discretization of hydraulic conductivity of hydrostratigraphic units: (a) MODFLOW model, (b) FEFLOW models of mine site with deformed, and (c) uniform layers.

6.4.3 Interpolation of Spatially Varying Properties

Interpolation of heterogeneous property distributions should only be done if there is a sufficient (large) data set and strong geological data supporting such spatial distributions, and if the interpolated property will not be adjusted during model calibration. For example, a tailings pile could be tested on a regular grid in many test holes and the resulting hydraulic conductivity interpolated. Generally, the accepted practice is to use the simplest interpolation method that is consistent with the known data. However, it is possible to construct different modelling scenarios with different parameter distributions resulting from various interpolation methods fitted to the data. The spatial variation can be calculated using various interpolation methods (e.g. distance weighed, linear, polynomial, or radial basis functions) or using more rigorous geo-statistical methods (e.g. kriging). This is rarely done except for research purposes. The simplest interpolation methods (e.g. linear trend over the study site) are preferred.

An interpolated hydraulic conductivity distribution is very impractical to calibrate, because the whole distribution must be changed in each calibration step. Therefore, a uniform distribution of K values within each unit or sub-unit is preferred for calibration of K values.

6.4.4 Anisotropy

Anisotropy is almost always specified over the whole hydrostratigraphic unit or locally within a specified model volume. There is almost never enough data to smoothly interpolate a spatial distribution of anisotropy. The orientation of the principal axes of anisotropy has a large effect on flow simulations, especially in steep terrain. It is important to recognize that there are different principal axis configurations for anisotropy:

- Vertical and horizontal in Cartesian coordinates – This anisotropy is aligned with geographic directions and the direction of gravity (Kx, Ky, Kz). It could represent horizontal bedding or fracturing of geological units that have been eroded or intruded, but where the anisotropy within the unit remains relative to horizontal or vertical axes.
- Parallel to slope of model layers – This is useful for deformed sedimentary geologic units or various types of sheet fracturing due to unloading of stress that occurs parallel to existing slopes and irregularly shaped units.
- Anisotropy specified in three dimensions using angles for each axis – This anisotropy direction is independent of Cartesian coordinates or model layer orientations and may be required in bedrock settings with significant tectonic movement.

It is common in models of alluvial aquifers and other sedimentary rock aquifers to specify vertical anisotropy of some assumed (or typical published) value. There should be a good discussion of the choice of anisotropy ratios and sensitivity analysis of this input. In steep topography where large gradients exist, anisotropy perpendicular to slope allows groundwater to flow easier in a downslope direction, while limiting water recharge and discharge perpendicular to the slope. The three-dimensional geometry of the model will determine how much of an effect anisotropy has and the sensitivity analysis will demonstrate whether the model results depend on, or are strongly influenced, by anisotropy assumptions.

6.4.5 Aquifer Heterogeneity

An important consideration in model parameterization is the representation of the natural variability of the aquifer system, i.e. the degree of heterogeneity and anisotropy of hydraulic properties (see discussion in Section 4). The degree of heterogeneity that should be incorporated in the model will depend on the complexity of the site and the modelling objectives but also on the availability of field data. At study sites with very sparse data, the modeller has no choice but to use homogeneous and isotropic assumptions. At sites where heterogeneity and/or anisotropy are well documented and important for the modelling objectives, this it should be explicitly included in the numerical model.

In most groundwater models for natural resource projects, aquifer heterogeneity is only considered at the domain scale. In other words, a uniform distribution of K values is assumed for each hydrostratigraphic units (or sub-units) (e.g. using an average K value). Smaller-scale heterogeneity, i.e. variations in K at the scale of an individual hydrostratigraphic unit (or subunit) can be modeled using geostatistical methods (see above), but requires detailed field information and is usually not considered for the large-scale models used in natural resource projects.

6.4.6 Aquifer Storage Properties for Transient Simulations

In transient simulations of groundwater flow, the storage properties of hydrostratigraphic units are used to determine the volume of released or stored water at each simulation time step. Unconfined storage is related to the release of water as the water table lowers (dewatering of the aquifer material); thus, it occurs only along the top boundary of the saturated flow system. Confined storage is related to the release of water as the head drops, because of the expansion of the water itself as the pressure changes. It is also related to changes in the solid skeleton of the aquifer (no dewatering occurs). In simulating changes in storage for transient systems, it is important that the unconfined storage occurs only at the top boundary (or top active layer), even if the water-table aquifer is divided into many layers. Most three-dimensional models (MODFLOW and FEFLOW) automatically control which storage coefficient is used based on the layer geometries and heads, thus ensuring the proper coefficient is used. Some model programs may require the modeller to specify the coefficient for each cell.

Storage properties are based on large scale pumping test results with at least one observation well. Not all natural resource sites have pumping tests completed, and in those cases, the storage parameters are taken from published properties for similar geologic formations or at nearby sites. These parameters can be adjusted through transient calibration, but should be included in sensitivity analyses.

6.4.7 Evaluation of Specified Properties

The selection of adequate parameter values and spatial discretization of hydraulic parameters for a groundwater flow simulation requires experience in hydrogeology and numerical modelling. The criteria include: the continuity of deposits, the type of depositional environment, the type of fractured rock, and the type of test data available, among others. As always, the objectives of the study also determine which features must be represented in the model and the level of detail required to adequately represent their effect on the flow system.

6.5 TRANSIENT SIMULATIONS

Transient models simulate time-dependent problems such as the impact of stresses over time. A transient simulation must begin with representative initial conditions and ends at a specified elapsed model time, which depends on the modelling objectives and time scale of the problem. Time is divided into time steps, and hydraulic head is computed at the end of each time step. Transient models are inherently more complicated than steady state problems, take longer computation time and create much larger data storage demands.

The special demands of transient simulations are as follows:

- The storage properties of the hydrogeological units must be specified.
- Initial conditions of hydraulic head distribution must be defined and must represent the site conditions.
- Boundary conditions (external and internal) must be adjusted to transient conditions (e.g. seasonal recharge flux rate, seasonal river stage variation, sea tides, changes in depth of mine pit or tunnel excavation, changes in mine site surficial materials, diversions of natural streams).
- Boundary conditions must be checked for interactions with hydraulic stresses which propagate over time especially at later times of the simulation.

6.5.1 Initial Conditions in Transient Simulations

Accurate definition of initial conditions for transient groundwater models is an essential part of conceptualizing and modelling transient groundwater flow (ASTM, D5610.1220124). Initial conditions represent the heads at the beginning of a transient simulation, and these conditions serve as a “boundary condition” in time for the transient groundwater model solution. Initial conditions for a flow system are usually represented by the hydraulic head distribution throughout the model domain (e.g. pre-mining conditions, average aquifer conditions before pumping). Initial fluxes may be also specified (e.g. pre-mining recharge rates). As the model simulation progresses, the new calculated changes in the hydraulic head through time will be relative to these initial heads.

Initial conditions are used only in transient simulations and are different from starting heads (or the initial guess) in steady-state solutions. In steady-state solutions, the starting heads affect the efficiency of the numerical solution, but the final solution is not dependent upon them; i.e. the same result should be observed independent of starting heads. In transient solutions, however, the initial conditions are the heads from which the model calculates changes in the system due to the stresses applied. Thus, the response of the system is directly related to the initial conditions used in the simulation.

There are two commonly used methods for defining initial conditions for transient simulations of hydraulic stresses: defining or simulating the steady state conditions or simulating long-term transient conditions prior to the modeled stresses in the predictive model.

Defining steady-state initial conditions is the preferred method if the hydrogeological system is in an approximately steady state prior to expected stresses. Any natural ground conditions without recent large disturbances to surface water drainage or extreme climatic change are typically assumed to be in steady state condition on an inter-annual time scale. Alternatively, a steady-state can be demonstrated with measurements. The numerical model can be solved in steady-state mode, and the steady-state solution imported into the transient model as part of the initial conditions. A steady-state model should be calibrated to the steady-state conditions.

Defining transient initial conditions is required if the hydrogeological system is not in steady-state equilibrium. This condition could occur (i) if the simulation is intended to simulate seasonal or other cyclic conditions where the system is never at a steady state (ii) in instances where there is a period of unknown stress that cannot be reproduced accurately, or (iii) when it is not feasible to simulate the entire period of record from a time of steady state. Under these conditions, it is important the initial conditions used do not bias the results for the period of interest.

The use of model-generated head values ensures the initial conditions and the model setup are consistent. In contrast, the use of field observations (say groundwater level time trends) for initial conditions can be problematic, in particular if the assumed initial head distribution will be inconsistent with the model setup (model setup precedes model calibration so there might be unanticipated adjustments in hydraulic heads once the model is run in transient mode).

In some cases, where the transient initial conditions are not representative, the model solution may be affected and the modeled response to stress may include a numerical model solution adjustment from initial time (at initial given conditions) to the model's boundary conditions—and not only to the applied stresses. The following situations are typically susceptible to this type of error:

- Slow and small expected response to applied stresses (e.g. aquifer is of low permeability, or stresses are small in magnitude or both).
- Highly time-variable hydrogeological system (e.g. highly-seasonal recharge and/or high variations in hydraulic heads).
- Changes in the hydrogeological system which are not accounted for in the initial conditions of the actual site, which may have occurred since the steady-state data was collected (e.g. river diversion or control, strong climatic change trends, or changes in groundwater use near the study site).

In other cases, the model is not significantly affected by initial conditions due to the high permeability of the aquifer and rapid equilibration to any stresses, whether natural or caused by natural resource extraction activities.

The determination of the importance and duration of erroneous effects or imperfect initial conditions can be accomplished by testing the effect of different initial conditions on the model under study. This test is accomplished by simulating the same system with the stresses and different initial conditions. When the simulations for all the different initial conditions produce the same result, then one can assume the influence of the inaccurate initial conditions is negligible for all the following time periods. There are published time constant formulas for estimating the aquifer response to transient stresses (Domenico and Schwartz, 1998), but it is recommended to model this response numerically for natural transient conditions of the site and to present graphically the results in support for the choice of initial conditions.

6.5.2 Initial Conditions in Transient Density-dependent Flow Simulations

There are two types of initial conditions: concentrations (densities) and equivalent freshwater heads. At each model node, the initial water density must be specified (sometimes specified as reference chloride concentration or another parameter concentration). At a maximum reference concentration, the density of water is assigned equal to that of saline water (as specified by the density ratio). At minimum reference concentration (background concentration), the water density is that of fresh water. Intermediate values are calculated numerically between these bounds.

6.5.3 Time Stepping

The intended use of the model is an important factor in choosing the length of stress periods and time steps. Many time steps are required to simulate a complex distribution of the head over time. Also, the size of the time steps has an impact on the accuracy of a model, particularly at the early stages of each applied stress. This is similar to the need for many cells to represent the spatial distribution of hydraulic head. It is important to incorporate enough time steps to allow the temporal complexity of the head distribution to be simulated (USGS, 2004).

Modelling programs such as MODFLOW and FEFLOW use stress periods to represent stress data as a function of time. A stress period represents a group of one or more time steps in which stress input data (e.g. pumping rates) are constant. A new stress period must start whenever it becomes necessary to change stress input data. If stress periods are too long, important dynamics of the stresses may be left out or poorly represented. For example, the Well Package of MODFLOW allows pumping rates for wells to change every stress period where the pumping within a stress period is constant (stepped function). In FEFLOW, the pumping rate can vary linearly or non-linearly over time, but the model solution is much slower due to small time steps used to vary the applied pumping stress incrementally.

There is a balance between time stepping accuracy and modelling time (and budget). For example, open pit excavation could be done progressively with very fine increments and appropriate geometry of pit depth and shape to achieve a precise solution. However, the simulation time would be very long and there is uncertainty about the actual excavation schedule which normally varies by many months, and for operational reasons, so does the pit geometry. The models are usually done by pit “stages”. Each stage is introduced at some discrete time during model simulation and the transient model shows how the groundwater system responds to each stage of excavation. A stepped approach of large applied stress is a simplified and reasonable representation of that type of boundary condition.

There is a need for performing a sensitivity analysis of the transient simulation results to the time stepping scheme of the model and the time-discretization of the applied stresses. Most modellers make several trial model runs with different time steps to check for effects on the final solution, but a formal sensitivity analysis may not be done. If a model is used to analyze the average response of a system over many years, then the applied stress might be represented as yearly averages using yearly stress periods. If a monthly or seasonal analysis is required, then the stress periods should also be small enough (say monthly or even biweekly) to represent that temporal variation in the recharge, the other boundary conditions, and the applied stresses.

There are published criteria for choosing the maximum time-step duration, which depends on the square of the model or element cell area and on “constants” such as the aquifer storativity and transmissivity. Most modelling programs have either automatic time stepping control, based on such criteria, or allow user-specified time stepping progression (1.2 to 1.5 is considered appropriate). It is the responsibility of the modeller to check the sensitivity of the modelling results to the time-stepping settings.

6.6 MODEL CONVERGENCE

Groundwater numerical models calculate the solution of large sets of simultaneous algebraic equations using sophisticated matrix solution techniques (“*solvers*”). Most of the solution techniques are iterative, where the solution is obtained through successive approximation, until a “good” solution has been obtained (the model *converged* on a solution). The criterion used in most iterative solution techniques is called the “head change criterion”. When the maximum absolute value of head change from all nodes during an iteration is less than or equal to the selected head change criterion, then iteration stops.

6.6.1 Accuracy of the Matrix Solution

When evaluating groundwater flow model results, the reviewer depends on model documentation and the reported head change criterion at model solution convergence. One means of evaluating whether an appropriate head change criterion was used is to examine the global mass balance for the model. If the error in the mass balance (e.g. total inflow minus total outflow divided by one half the sum of the inflow and outflow) over the entire model domain is small, usually less than 0.5 percent, then the head change criterion is assumed to have been sufficient. If the error in the mass balance calculations is significant, then the model solution was not good enough.

Even if the head change criterion is met and the global mass balance error is small, the model solution may not be appropriate for the system under investigation. Two potential reasons are that some models can either be mathematically non-unique or very nonlinear. The mathematically non-unique problem is usually a poorly posed problem, where a model has only specified-flow boundary conditions and no other boundary condition that specifies a head or datum (such as, constant head, river stage, general head boundary, etc.). In this type of problem, there is a family of solutions all with the same gradients, but different absolute heads. The matrix solution technique may not converge or it may converge to one of the infinite number of possible solutions.

The accuracy of the matrix solution is usually not an issue with groundwater models that meet the head change criterion and have small mass balance errors. It is important when using nonlinear models. In nonlinear problems, the solution affects the coefficients of the matrix being solved; thus, the solution affects the problem being solved. As a result, the manner in which the iterative solution technique approaches a solution can affect the final solution. The rate of convergence and the method of making cells inactive is usually considered by the modeller, but it is not easy to determine if the solution is correct.

6.6.2 Methods Used to Improve Solutions

The matrix solution can be improved by lowering the head change criterion, adjusting iteration parameters (if the solution techniques use iteration parameters), using different starting heads for steady-state simulations, or using a different solution technique. Some models do not converge smoothly, and modellers use non-standard methods to obtain a model solution. As long as the non-standard method does not violate any important hydrological processes, they are usually transparent to the final solution and are appropriate. However, these non-standard techniques should be evaluated to determine whether they cause potential errors to be introduced into the model solution.

Examples of non-standard modelling methods to improve a solution include:

- Saving of intermediate solutions that have not yet converged and changing matrix solution parameters when restarting the model.
- Making a nonlinear water-table simulation linear by fixing the saturated thickness of the model to avoid cell re-wetting and drying problems as well as head oscillations.
- Obtaining a steady-state solution by using storage to slow convergence and dampen the approach to the solution through simulating a long transient time period.

SUMMARY POINTS FOR MODEL SETUP

1. Selecting the size of the cells or elements is an important step in numerical model design. Model grids and meshes need appropriate design to allow representation of the most important features in groundwater system, with enough detail to answer the modelling objectives. Vertical discretization should be sufficient to represent the hydrostratigraphic units and hydraulic property distributions, and provide enough intermediate model cells to produce good three-dimensional solution.
2. The boundary conditions determine where the water enters and leaves the system, thus their selection is critical to an accurate model. Errors in boundary conditions may cause serious errors in model predictions.
3. Model domain boundaries can be physical or hydraulic boundaries, but the use of a hydraulic boundary should be evaluated carefully to determine whether its use would cause unacceptable errors in the model.
4. Hydraulic properties of hydrostratigraphic units should be assigned based on representative ranges of values with good support from available data. These parameters have a significant effect on model results and are adjusted during model calibration.
5. Interpolation of heterogeneous property distributions should only be done if there is sufficient (large) data set and strong geological data supporting such spatial distribution, and if the interpolated property will not be adjusted during model calibration.
6. Anisotropy can be used if there is good geological justification for this property. The orientation of principal axes of anisotropy has a large effect on flow simulations, especially in steep terrain.
7. In transient simulations of groundwater flow, the storage properties of hydrostratigraphic units are used to determine the volume of released or stored water at each simulation time step. Steady-state models do not use storage properties.
8. Accurate definition of initial conditions for transient groundwater models is an essential part of conceptualizing and modelling transient groundwater flow. The use of model-generated head values ensures that the initial conditions and the model setup are consistent.
9. There is a need for performing a sensitivity analysis of transient simulation results to time stepping of model and time-discretization of applied stresses.
10. The accuracy of model solution depends strongly on head change criterion, and the quality of solution can be assessed by examining the simulated water balance error.
11. Some models do not converge smoothly, and modellers use non-standard methods to obtain a model solution – if used, these procedures should be documented.

7 MODEL CALIBRATION & VERIFICATION

7.1 INTRODUCTION

7.1.1 Scope

This section describes model calibration. Topics covered include:

- Concepts of model calibration (definitions, calibration process)
- Calibration targets, calibration parameters
- Parameter estimation techniques
- Evaluation of calibration results (goodness of fit criteria)
- Model verification (testing of calibrated model).

7.1.2 Definitions

Model calibration is defined as the process of refining the numerical model's representation of the hydrogeological framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulation and observations of the groundwater flow system (ASTM, 2008).

The following are two definitions of a calibrated model:

- *A calibrated model* is a model that has achieved a desired degree of correspondence between the model simulations and observations of the physical hydrogeological system (ASTM, 2008).
- *A calibrated model* adequately represents the system conditions such that an answer to the question posed by the modeller or the regulator is possible (Woessner and Anderson, 1996).

Observed values, observations or sample data, describing the state of the groundwater system measured in the field or the properties of the system. Examples of observed values include the elevation of the water in a piezometer, the flow rate at a spring, or the concentration of contaminants in a water quality sample. Field parameter values usually refer to hydraulic conductivity, transmissivity, and storage properties determined from analysis of hydraulic tests.

Calculated values are the output from the numerical model. Examples include hydraulic pressure distributions, flow rates, and contaminant concentrations. In a predictive model, calculated values are the "predicted values".

Calibration parameters are those model parameters (hydraulic properties or boundary conditions) whose values are adjusted during the calibration process.

Calibration targets are observed values which are matched to corresponding calculated values during model calibration process. For a transient model this is sometimes called "*history matching*".

7.1.3 Calibration Process

The calibration process involves refining the hydrogeological conceptual model and the numerical model parameters to achieve the desired degree of correspondence between the model simulation results and the observations of groundwater flow system. The degree of difficulty of model calibration depends on the amount and the quality of measured data, the complexity of processes being simulated, and the complexity of the conceptual model. Modeller experience and computing power also has significant effect.

There is always some initial conceptual model of the groundwater flow system, and usually some parts of this model are adjusted during this process. For a given conceptual model configuration, the calibration process consists of adjustments to hydraulic parameters and recharge fluxes within a reasonable range of values. If the hydraulic properties adjustment fails to provide adequate calibration result, the conceptual model is modified again (e.g. changing a boundary condition).

The choice of evaluating alternative conceptual models and calibrating each model depends on project objectives and budget. There is always more than one conceptual interpretation (feasible conceptual model) of a groundwater system, and it is important to evaluate many lesser known aspects of the conceptual model (Poeter et al, 2008). However, in most modelling projects usually only one conceptual model is presented along with only one final calibration result. It is acceptable to present only one calibrated model based on one selected conceptual model configuration, but the assumptions and limitations of alternative conceptual models should be at least discussed. Where it is not clear which conceptual model is the most valid, and there are high risks and consequences to model results, it may be advisable to evaluate two or more conceptual models. This would entail constructing alternative mathematical models, to calibrate each separately, and to present alternative predictive models.

For the purpose of this section it is assumed that the modeller has a robust and representative conceptual model before proceeding to implement the calibration guidelines of this section. If multiple conceptual models are considered reasonable, each should be carried through calibration for use during uncertainty analysis (see section 8). Case study 2 provides a good example of the use of multiple conceptual models (refer to Section 7.7.1).

The following aspects of model calibration should be documented to facilitate review of model calibration:

- The details of calibration statistics are presented, including a complete description of calibration residual distribution.
- Major assumptions about data interpretations are listed in a prominent place in the model report. Model calibration limitations are discussed or listed (e.g. explanation of large calibration residuals).
- An initial sensitivity analysis to calibration parameters and ranking of most important parameters (see Section 8 for more details on model uncertainty and rigorous sensitivity analysis process).
- There is a good discussion on the alternative conceptual models as relating to model calibration results.

7.1.4 Calibration Parameters

The following is a list of calibration parameters commonly used for model calibration:

- Hydraulic properties are selected by identifying zones of similar aquifer hydraulic properties based on geology and aquifer testing.
- Recharge flux is estimated based on regional or local analysis of precipitation and water balance, ground cover type, elevation, soil properties, etc.

- Discharge flux of groundwater to surface drainage network.
- Other groups of inputs that can be parameterized for the project objectives.

For each calibration parameter, the range of possible realistic values that parameter may have in the physical hydrogeological system should be identified prior to model calibration.

7.1.5 Calibration Targets

The most common observed values used as calibration targets in groundwater flow models are:

- Hydraulic heads (water table elevation in unconfined aquifer, potentiometric surface or pressure distribution in confined units) at one or more points in space, and may include multiple observed heads in many hydrogeological units.
- Groundwater flux as observed discharging to surface, creeks, lakes or mine workings (pits, underground workings). Other fluxes sometimes used for model calibration include net infiltration to water table (recharge), observed seepage losses (from ditches, streams, lakes), and observed volumes pumped from wells or injected into an aquifer.
- Water density or salinity in density-dependent flow models.
- Concentrations of contaminants in contaminant transport models (see Section 9).

Temperature in groundwater flow and heat flow coupled models are not included in these guidelines, however, water temperature is a useful natural tracer which is used in transient analyses to estimate groundwater recharge sources and lag times.

7.1.6 Calibration Data Requirements

The observed data used as calibration targets must have sufficient spatial distribution for all models, and sufficient temporal distribution for transient models. A large number of uniformly distributed calibration targets, each having small associated error, will increase the likelihood of obtaining a unique calibration, as will the use of groundwater fluxes.

The following is a list of common problems with calibration target data distributions:

- Hydraulic head data points are clustered and not widely distributed across the site in the model domain. A typical example are exploration boreholes, which were also tested and monitored in ore deposit areas, or clusters of engineering boreholes in proposed waste rock dump or other engineering study areas.
- Monitoring wells may also be present in easy to access areas such as valley bottoms, especially near existing roads and streams. Steep slopes and mountain tops are typically not monitored due to difficulties in monitoring well installation, but the most important data for model calibration of recharge-driven model is in the steep slopes and mountain tops.
- Having many points along rivers or lakes does not help the calibration because the surface waters are usually represented with boundary conditions and the model head is set (not calibrated) in those areas.
- Groundwater discharge fluxes (base flows in streams) may be monitored in adjacent catchments, or too far downstream from the model site and affected by runoff from other catchments.

- Carefully planned field programs may not anticipate site complexities which are evaluated later in the modelling process (e.g. faults in fractured rocks).

The modeler (and model reviewer) should be conscious of these limitations with potential calibration target data and take these limitations into consideration when selecting calibration targets and evaluating model calibration.

7.1.7 Calibration Data Quality

Difficulties in calibrating the numerical model to observed field data may indicate a problem with the quality of the monitoring data. In principle, all monitoring data should have been checked prior to model calibration. However, some data errors will not be apparent until they show significant discrepancies with the simulated response during model calibration.

The error bounds and calibration targets should be set before the calibration process. Sources of error in each calibration point should be assessed and quantified to assign relative weights to data points before starting calibration.

Data quality issues that should be considered include:

- Representativeness of water level
- Transient variation of hydraulic head
- Positional survey error
- Monitoring piezometer design uncertainty
- Water level measurement error
- Representativeness of discharge measurements (locations of measurements)
- Streamflow measurement method error (base flow measurement may be difficult if the streams receive continuous runoff from precipitation or ice melt)
- Assumptions for hydrograph analysis (streamflow data)
- Dewatering system statistics (e.g. from underground mine) or open pit water level changes (mine inflow); groundwater extraction statistics (for pumping systems)
- Representativeness of recharge measurements (locations of measurements)
- Assumptions in infiltration modelling (soil types, materials used as covers, geology, scale, precipitation inputs, climate, etc.)
- Temporal variation in water density and salinity (e.g. during active salt water intrusion in coastal aquifers, tides)
- Misinterpretations of geophysical survey results.

Appendix F provides more details for each data error type.

7.1.8 Steady-state vs Transient Calibration

Steady-state simulations are used to model equilibrium conditions representing the “average” hydrological balance, or conditions where aquifer storage changes are not significant.

Transient simulations are used to model time-dependent problems, and/or where significant volumes of water are released from or taken into aquifer storage (for example a pumping test, highly seasonal flow field).

Data requirements for transient models depend on the modelling objectives, but in general there should be transient data on the same time scale, and with the same temporal resolution as the modeled stress and duration, such as:

- The data set used for transient calibration should include pumping test data, and/or sufficient duration of regular monitoring data that shows the natural seasonal variations and responses to artificial stresses applied during natural resource extraction projects.
- The transient data should be available for several spatially distributed representative locations throughout the model domain.
- Different hydrostratigraphic units should be tested and several tests in different locations to have more confidence in model calibration uniqueness.

Case study 3 provides a good example of the use of steady-state and transient calibration (Section 7.7.2)

7.2 CALIBRATION TECHNIQUES

Calibration of a numerical model may be done by manual *trial-and-error* or by *automatic parameter estimation* methods, or a combination of the two.

7.2.1 Manual Trial-and-Error Calibration

In trial-and-error calibration, the modeller changes the model input parameters manually in order to improve the correlation between model output parameters and field parameter values.

Manual trial-and-error calibration may proceed by changing one parameter at a time (similar to a sensitivity analysis, see Section 8) or by trying different combinations of parameters. Manual trial-and-error calibration is labour-intensive and time consuming but is the most common method of calibration.

Manual trial-and-error calibration gives the modeller significant insight into the factors controlling the system and should always be part of model calibration, in particular during the early stages when the conceptual model has not been finalized.

7.2.2 Automated Parameter Estimation

Automated parameter estimation involves the use of one or more computer codes specifically developed to undertake model calibration. The following are inverse software codes developed by the USGS for use with MODFLOW:

- UCODE_2005 – MODFLOW-2000 Observation, Sensitivity, and Parameter-Estimation Processes (Poeter et al, 2005).
- PEST – Parameter Estimation (Doherty, 1994, 2005).
- Various user interfaces to MODFLOW such as Visual MODFLOW (SWS, 2011), Groundwater Vistas (Scientific Software Group, 2011) and GMS (Aquaveo, 2011) also have PEST capabilities (see Section 5).

Extensive guidelines for automated and effective model calibration have been developed by Hill and Tiedeman (2007). Difficulties in automated calibration are resolved as follows (Poeter et al, 2005):

- Reconsider the conceptual model.
- Confirm the accuracy of field data.
- Modify the input parameters.
- Use a different numerical code.

Automated parameter estimation should be used only after completion of at least some initial manual calibration to: (i) confirm that the conceptual model is reasonable; and (ii) to bracket the range of model parameters to be varied in automated parameter estimation.

The use of automated parameter estimation techniques requires significant specialized experience by the modeller. If not used properly, this method may yield incorrect results (very good calibration statistics but incorrect parameter distributions) or no result at all (non-convergence).

7.2.3 Non-Uniqueness

Non-uniqueness during model calibration arises because many different sets of model input parameters can produce nearly identical model outputs (Brown, 1996). Any combination of groundwater flow rates and hydraulic conductivities input to the model that has the same ratio as the actual flow rates and hydraulic conductivities in the aquifer will produce nearly identical hydraulic head distributions as output. Hence, a good matching of measured and modeled hydraulic heads during calibration does not guarantee that the hydraulic properties used in the model are close to those actually found on site.

Non-uniqueness cannot be eliminated but it may be reduced. Methods to address the non-uniqueness problem include:

- Restrict the range of input parameters to values that are consistent with field values.
- Calibrate the model to a range of distinct hydrological conditions (e.g. seasonal climate variation and extreme conditions, and ranges of induced stresses.
- Use measured groundwater flow rates (e.g. stream base flow) as calibration targets (in addition to hydraulic heads).
- Use data that has sufficient spatial and temporal distribution.

Figure 7-1 illustrates the concept of non-uniqueness, as well as the value of calibrating to multiple datasets. The different lines associated with each dataset represent possible hydraulic conductivity and flow combinations that would provide the same calibration result.

The area within the red circle represents a more constrained range of flow and K value combinations that would fit multiple datasets. While multiple combinations are still possible, the overall calibration is improved. Model confidence improves as more datasets are used to calibrate the model. Therefore, the variety and distribution of available data are key model attributes to be considered by the modeller and reviewer.

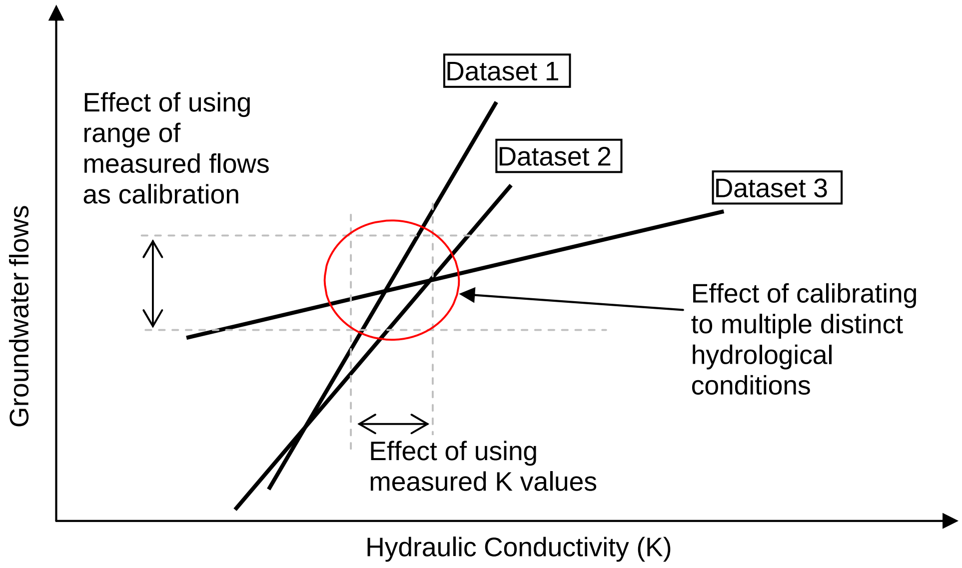


Figure 7-1: Addressing the non-uniqueness problem (after Ritchey and Rumbaugh, 1996)

7.3 EVALUATION OF CALIBRATION RESULTS (GOODNESS OF FIT)

This section describes methods for evaluating the calibration results. This includes a discussion of calibration acceptance criteria and descriptions on various qualitative and quantitative methods for comparing field measurements to the same parameter as calculated with the model.

7.3.1 Calibration Acceptance Criteria

The calibration acceptance criteria refer to model goodness of fit using quantitative (statistical) thresholds and qualitative goodness of fit requirements. These criteria are project-specific, depend on the modelling objectives and data availability, and should be defined before model calibration. Subsequent changes in calibration criteria should be justified.

The regulator reviewing a model should examine calibration criteria or targets to determine that the proponent develops a valid, robust, and rigorous model, based on an appropriate conceptual model and calibration procedures. These guidelines support the use of a-priori specified quantitative acceptance criteria used in combination with qualitative calibration performance measures.

These guidelines do not set prescriptive calibration criteria. It is recognized that the advantages of prescriptive calibration criteria include:

- Unambiguous performance measure to judge model calibration.
- Desirable for regulating agencies, as it sets out the required performance specifications.

Prescriptive criteria may, however, involve the following disadvantages that make them less desirable than project-specific criteria:

- A potential overemphasis on or even erroneous calibration. This happens if a modeller adjusts aquifer properties to ensure a better match of simulated heads with field observations, when in fact the field data are wrong.
- Achievement is contingent on model complexity, which in turn depends on geological knowledge, data availability and quality, deadline, budget, and model complexity.

7.3.2 Qualitative Calibration Evaluation

Examples of spatial distributions used in qualitative evaluation of model calibration include:

- Patterns of groundwater flow based on modeled contour plans of aquifer heads.
- Patterns of aquifer response to variations in hydrological stresses (hydraulic head hydrographs).
- Distributions of model aquifer properties adopted to achieve calibration.

A qualitative evaluation of model calibration can also take into account the specific location of calibration targets, and potential differences in their relative contribution to model calibration. For example, residuals for head values near specified head boundaries are constrained by the nearby boundary and cannot vary easily in the model simulation, while heads near hydraulic boundaries can vary greatly as a result of variation in hydraulic properties.

7.3.3 Statistical Calibration Evaluation

There are many methods for quantitatively evaluating the goodness of fit between measured and modeled parameters. The proponent is encouraged to select statistical methods applicable to a specific groundwater modelling project. The following are considered the minimum statistical evaluations that should be reported.

7.3.3.1 Residuals

Mathematically a residual is simply the difference between a measured and a calculated value (or between a calculated and a measured value). In groundwater modelling, residuals may be calculated by comparing measured versus calculated heads, flow rates, constituent concentrations, or any other reasonably comparable parameter. Generally in groundwater flow modelling, residuals are calculated for head, and thus in this subsection reference in made only to hydraulic head.

The hydraulic head residual (r_i) is the difference between the calculated (modeled) head value (h_c) and the measured head value (h_m) at point i. It may be expressed by either of these equations:

$$r_i = h_c - h_m \qquad \text{or} \qquad r_i = h_m - h_c$$

Weighing coefficients (W_i) can be applied to account for confidence in the data quality. *Wi* can vary from 0 to 1. If all points are weighed equally, *Wi* is equal to 1 for each point *i*. Poor quality measurements may be excluded, or in case of clusters of points, the most representative and best quality measurement used and others in the cluster excluded.

Methods for establishing acceptable residuals include:

- Judgment
- Kriging (variance estimate at each observation point)

- Trend analysis (heterogeneous aquifers defined by sub-regions only).

In general, the residual should be a small fraction of the difference between the highest and lowest heads across the site (ASTM, 2008). Acceptable residuals may differ for different hydraulic head calibration targets.

7.3.3.2 Normalization

In order to standardize average measures with different units or scales, a non-dimensional *normalized* measure is used as in the following equation:

$$\text{Normalized Mean Residual Error} = \frac{\text{mean residual error}}{\max(h_m) - \min(h_m)} \ (\%)$$

7.3.3.3 Average Residual Error Measures

The Root Mean Squared Error (RMSE) and the Normalized RMSE as in these equations may be used:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[W_i(h_c - h_m)]_i^2} \qquad \text{NRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}[W_i(h_c - h_m)]_i^2}}{\max(h_m) - \min(h_m)} \ (\%)$$

The Mean Absolute Error (MAE), or the Normalized Mean Absolute Error (NMAE) is also commonly used:

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|W_i(h_c - h_m)_i| \qquad \text{NMAE} = \frac{\frac{1}{n}\sum_{i=1}^{n}|W_i(h_c - h_m)_i|}{\max(h_m) - \min(h_m)} \ (\%)$$

In mountainous regions, normalized errors may be more appropriate to account for significant variation in water level elevations. Alternatively, different measurements may be used to remove effects related to elevation. For example, calibration may be based on depth to water instead of water level elevation. The same residual error measures listed above can be used for either type of water level measurement.

7.3.3.4 Correlation Coefficient

The correlation coefficient (R) is a measure of the correlation of two data sets. R^2 is the coefficient of determination. R calculation requires the mean and standard deviation of the observed and calculated values and evaluates the residuals relative to the mean. Both R and R^2 vary from 0 to 1 (1 meaning perfect linear relationship).

In hydrogeological modelling, a model is considered calibrated when the correlation coefficient is at least 0.95. However, R is very sensitive to outliers (very large positive or negative residuals), and often high R values may result if the data has strong auto-correlation (e.g. hydraulic heads correlated to topography on a high topographic relief site). Also, an R value is meaningful if there is a randomly distributed scatter of residuals and a sufficient large number of points (e.g. a high R statistic based on two calibration points indicates a perfect calibration to insufficient data set).

7.3.4 Graphical Calibration Evaluation

These guidelines recommend the use of graphics to enhance the qualitative evaluation of model calibration. The following subsections provide examples of graphical means to evaluate (and illustrate) model calibration.

7.3.4.1 Scatterplots

To show that there is no systematic error in the spatial distribution of differences between modeled and measured heads, the modeller should compile a scattergram (scatterplot). Scatterplots of residuals are graphical representations of goodness of fit of individual calibration targets (usually head values) associated with average error statistics. These plots show measured hydraulic heads on the horizontal axis, and modeled hydraulic heads on the vertical axis, with one point plotted for each pair of data at observation points. All the points should occur with a minimum degree of scatter about the line of perfect fit. Scatterplots are useful in detecting:

- Outliers
- Clustering
- Trends.

The scatterplots should be clearly presented and the graph scales clearly visible. Some model calibration plots appear to show good fit and the residuals are small in appearance on graph, but the magnitude of residuals depends on the graph scales. Confidence intervals should also be plotted.

Many other types of plots may be used to demonstrate the spatial distribution of error; examples are given in modelling text books (e.g. Hill and Tiedeman, 2007; Anderson and Woessner, 1992; and Spitz and Moreno, 1996).

Figure 7-2 a-d illustrate types of scatter plots and histograms used at two sites with high topographic relief. In Figure 7-2a, results suggest a good fit with normalized residuals of 4.9% and R^2 of 99%, Figure 7-2b shows a scatter plot of residuals for site 2. Similarly to Figure 7-2a, residuals based on calculated vs. observed head elevations appear acceptable. The residual histogram for this site (Figure 7-3c) shows the range of residuals more clearly. Histograms are described in the next section. Figure 7-3d presents the residuals as depth to water, which removes the influence of elevation. In contrast to nRMSE presented for data based on elevation in Figure 7-3b, nRMSE is significantly higher (23% for depth to water vs. 3.5% for elevation).

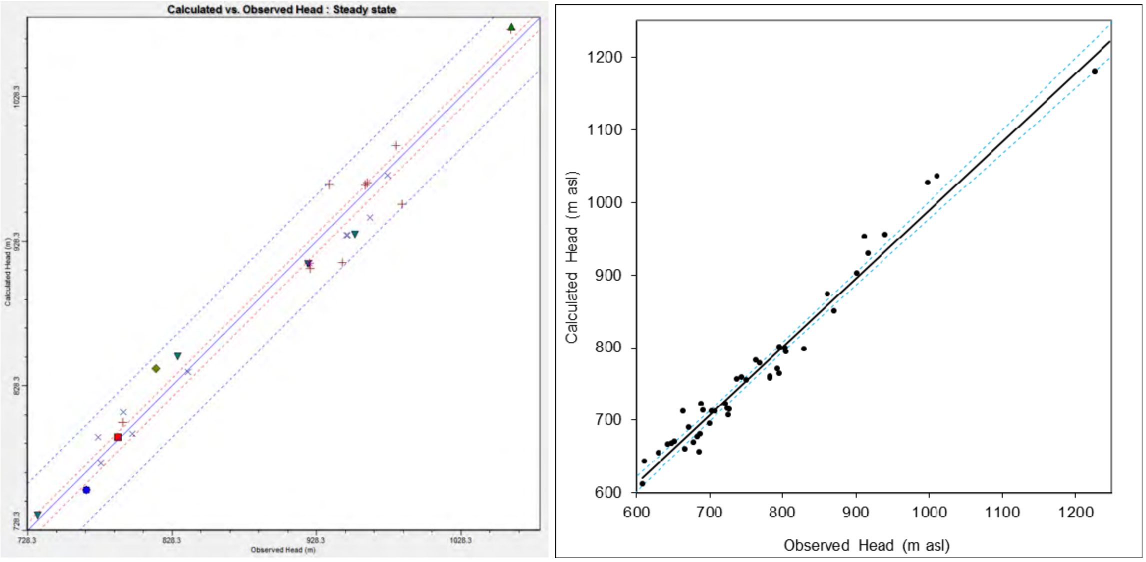
It is a good practice to categorize calibration points based on relative importance. For example, calibration points near boundary conditions (which are likely to be influenced more by the boundary than aquifer parameters) or which are clustered (and therefore are redundant), can be identified. Figure 7-3 provides examples of scatterplots illustrating this concept.

7.3.4.2 Histograms and Cumulative Frequency Plots

A histogram of residuals should be normally distributed with a mean close to zero. Figure 7-2c is an example of such a histogram.

(a) Heads at Site 1

(b) Heads at Site 2

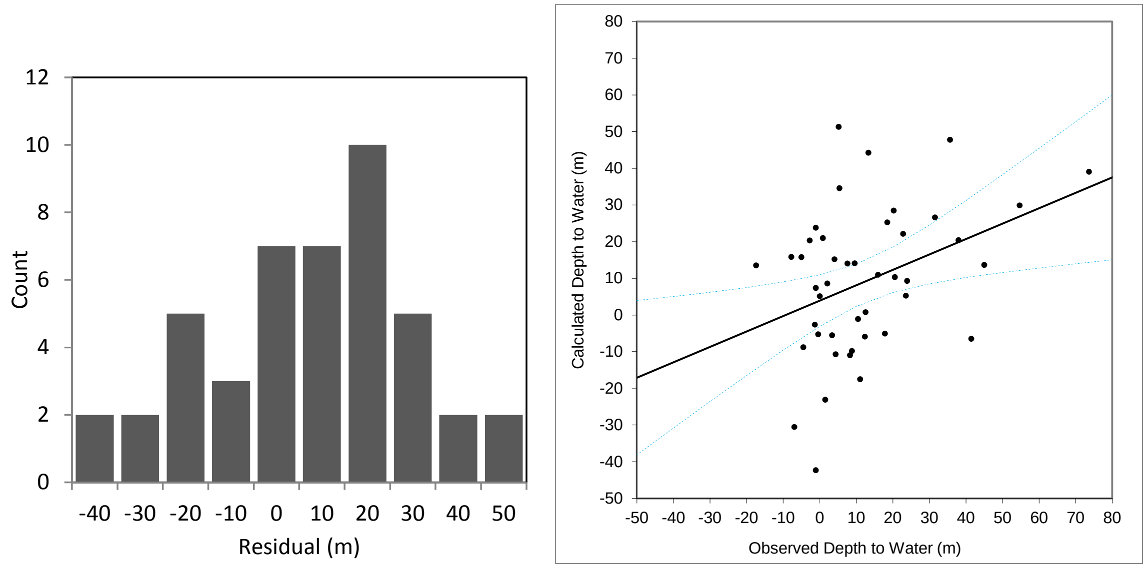


nRMSE = **4.9**%

nRMSE = **3.5**%

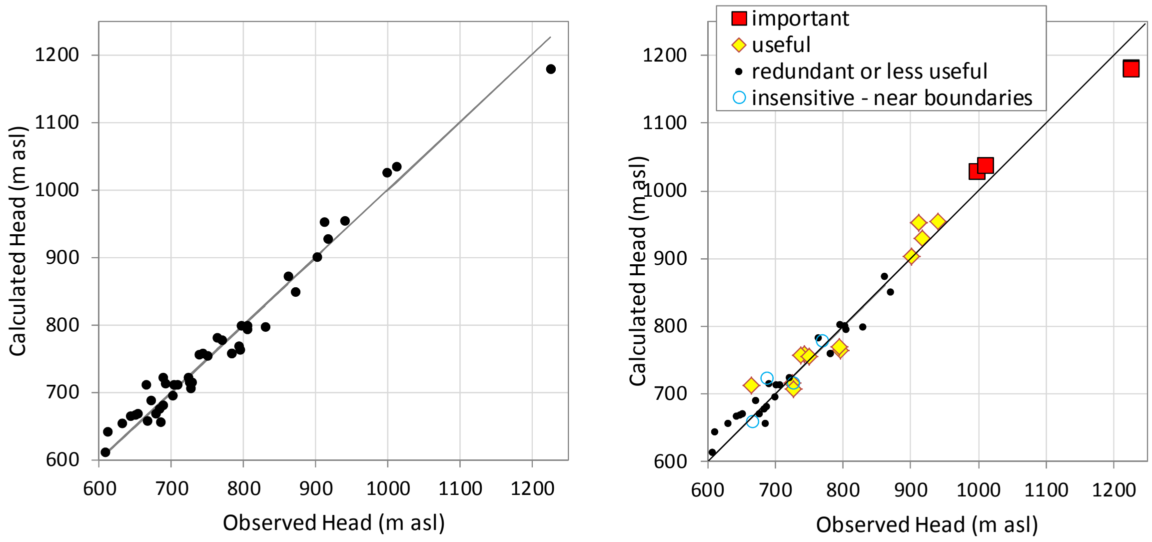
(c) Head Residuals at Site 2

(d) *Depth to Water* at Site 2



nRMSE = **23.4**%

Figure 7-2: Examples of residual presentation plots presented for two sites with high topographic relief: (a) poorly presented graph (b) clearly presented graph (c) histogram of residuals (d) plot of residuals for depth to water



RMSE = 21.3m
nRMSE = **3.5**%
r^2 = 0.99

min h_c = 608m
max h_c = 1230m

min residual = -46m
max residual = +48m

Figure 7-3: Example of categorized scatterplot: (a) all points, (b) categories of data points by importance.

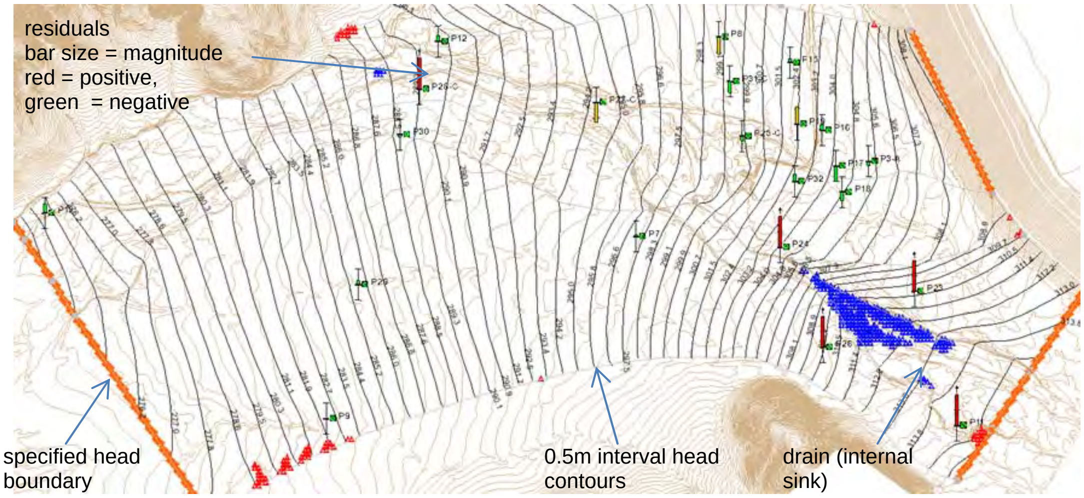
7.3.4.3 Spatial distributions of residuals and head contours

There are many ways of displaying the spatial distribution of residuals from calibration. Different symbols and colors can be used to enhance the perception of magnitudes and signs of residuals, and their location in relation to other features and boundary conditions.

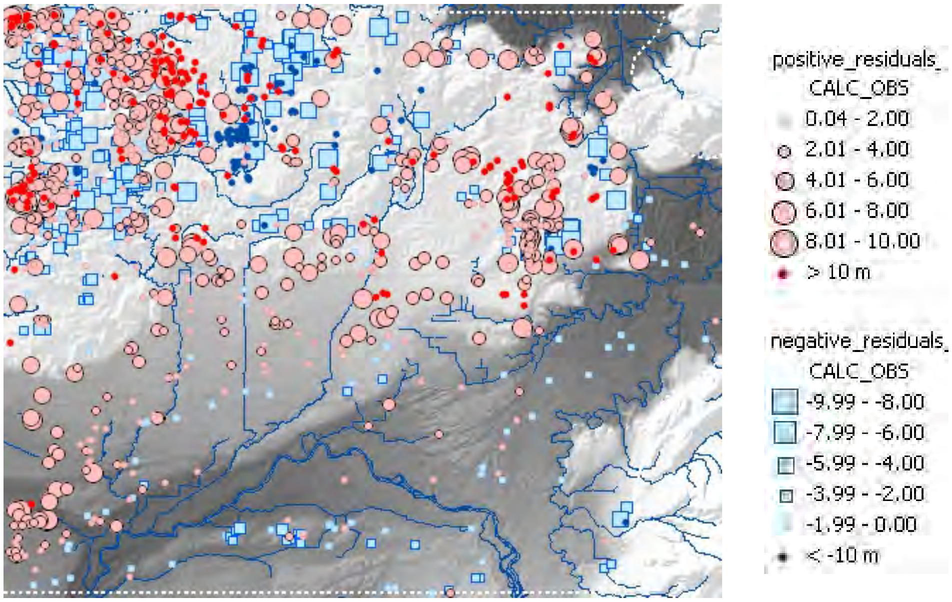
Figure 7-4 a,b provide examples showing a map-type graphical distribution of errors. In Figure 7-4a, a calibration bias can be seen on the upstream portion of the model domain. The calibration targets of wells P24, P23, P26 and P11 all appear in red, indicating the elevation of the simulated heads at these locations is above 200% of the calibration target (in this case set to +/- 0.5 m). Figure 7-4b illustrates the use of scaled “bubble plots” to show the spatial distribution of residuals. Both of these examples illustrate how showing the spatial distribution of residuals provide insight into what areas of the model have better or worse fit, as well as where the model may have less or more calibration points.

Model cross-sections are also useful to present modeled and observed water table, locations of wells, hydrostratigraphic unit thickness and geometry, vertical flow paths and contours. Cross-sections are particularly useful in steep slopes near boundary conditions and features of interest (e.g. pits, tailings dams, waste rock piles). Figure 7-4c is an example of a cross-section type calibration graphic. In this example, calibration bias in higher elevation areas can be observed (higher elevation areas have different residual error than other areas).

(a) Map of residuals and head contours



(b) Bubble plots scaled to residuals overlain on map (Scibek and Allen, 2005).



(c) Cross-section plot showing graphical water table representation and calibration residuals.

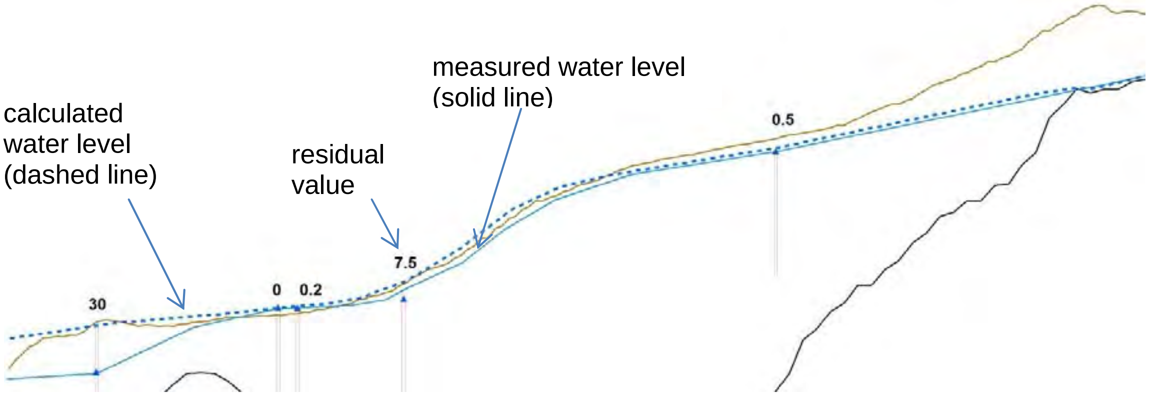
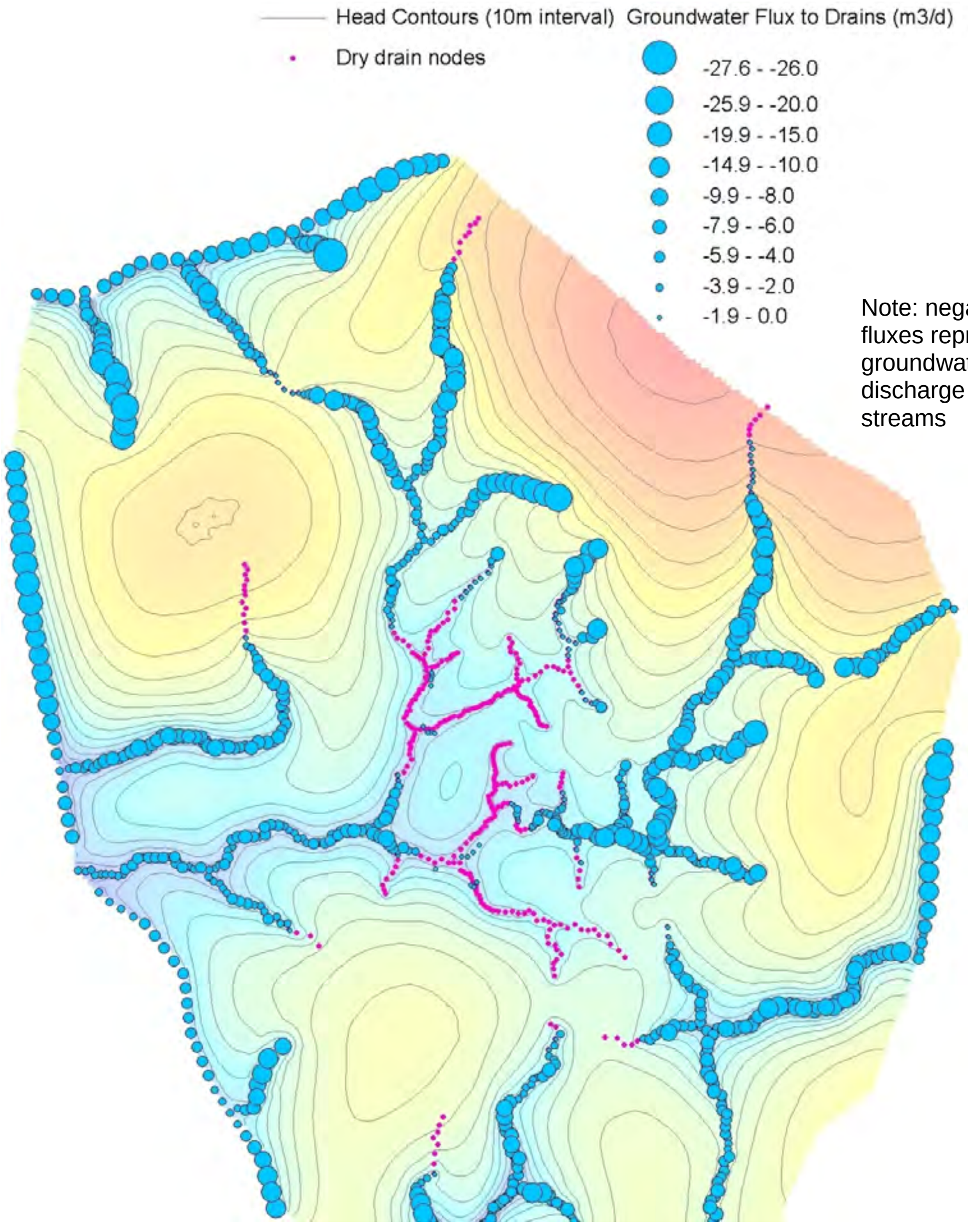


Figure 7-4: Examples illustrating spatial distribution of residuals

7.3.4.4 Spatial distribution of fluxes to and from sources and sinks and boundaries

The distribution of flux magnitudes and direction should be graphed on a map to identify which boundary conditions are taking water or producing water. Figure 7-5 is an example of this type of graphic for a model in a mountainous terrain. Dry or inactive drains are identified and the magnitudes of groundwater fluxes toward receiving drains are easily compared. The quantities should be summed up for streams and rivers for which base flow data is available, and compared to modeled and measured quantities. The model should be calibrated to generate the same base flow as observed (within error bounds). The use of fluxes for calibration (in combination with heads) provides an additional constraint to the model and makes the solution more unique.



Note: negative fluxes represent groundwater discharge into streams

Figure 7-5: Example of graphical water budget representation

7.3.4.5 Transient Time Series Plots

Transient calibration can provide improved confidence in model results, particularly in cases where seasonal effects may be important, but transient calibration can be subject to different issues than steady-state calibration.

There are cases when a simulated hydraulic head hydrograph might agree very well with a measured head hydrograph in pattern and amplitude, such that the transient datasets are parallel, but differ in absolute magnitude. Figure 7-6 presents an example of hydraulic heads near a river responding to river stage variation. The average residual error statistics in calibration B suggest a poor calibration, when in fact the modeled transient response might be very good. In this example, the time series regression and correlation have a high coefficient of determination and a good model fit, despite the observed absolute difference in hydraulic head elevation (in this example, calibration point B).

Another technique is the standard correlation function (r) between two time series (Zheng and Bennett, 1995). A more advanced definition of correlation with lag might show whether a model is responding too fast or too slowly. Note that time series regression compares the residuals between observed and regression model (linear usually), so as long as the two time series of water levels vary in time similarly (despite systematic shifts or amplitude changes), the correlation and coefficient of determination will be high. This is a different concept than a simple error measure such as nRMSE. The nRMSE is useful for evaluating spatially distributed residuals, while time series correlation statistics are useful for comparing time series variation with time.

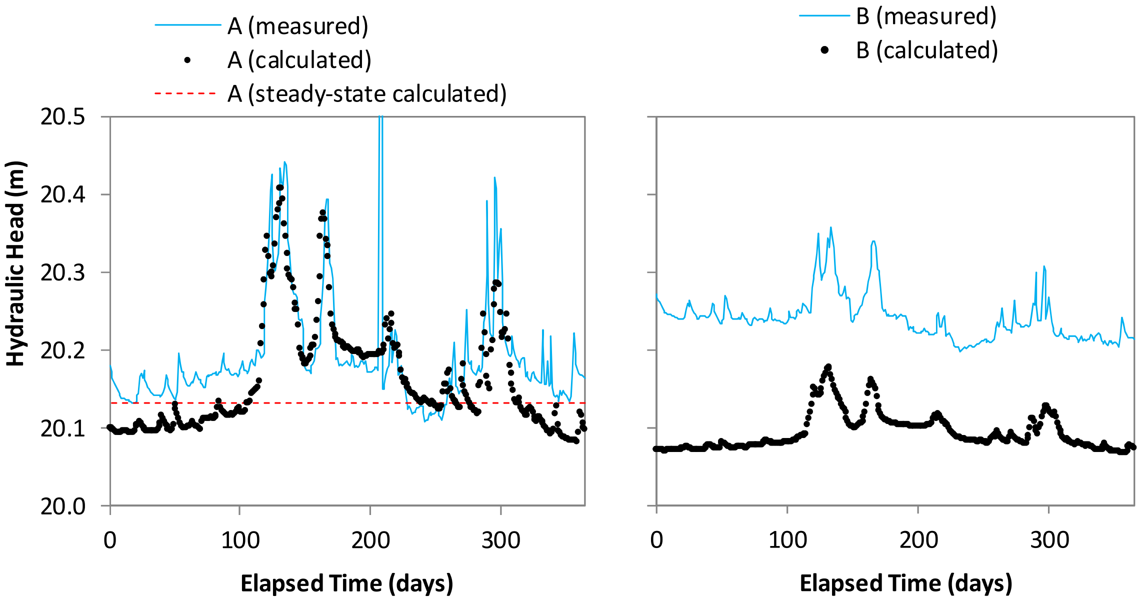


Figure 7-6: Examples of transient calibration presentation for a site located near a small river, showing river-aquifer interaction and transient hydraulic head calibration time series: (a) good calibration except to high outliers, (b) good calibration to variation in time but with shifted datum

Aquifer heterogeneity and model initial conditions can also effect transient calibration. The transient model fit may vary greatly from point to point due to aquifer heterogeneity, as shown in example from Abbotsford-Sumas Aquifer in Figure 7-7a (Scibek and Allen, 2005). In this example there is also some variation in recharge due to difference in soil types, but a high permeability homogeneous aquifer water table is very smooth despite small scale spatial recharge variation. Large steps in water table result in aquifer heterogeneity (or structural control if in fractured rock).

The transient model may also start with wrong initial conditions (Figure 7-7b) but the overall fit can be reasonably good at later times. What is important is the match in amplitude of variation, no lag in response, good initial conditions, and responsiveness to smaller frequency “events”. The vertical datum is of lesser importance in the transient model if the regional gradients are sufficiently calibrated.

The average residual error statistics can be applied to drawdowns (or depth to water) rather than elevation heads, where the drawdown is normalized to the initial head or some other datum. Measured and simulated drawdowns would have separate reference datum. An example of drawdown calibration in four pumping wells is shown in Figure 7-8. The flow model was calibrated to 11 pumping wells by changing aquifer properties in sub-zones. A model does not have to fit all observation points, but a good model will fit most of them and especially the most important points (judged by the modeller).

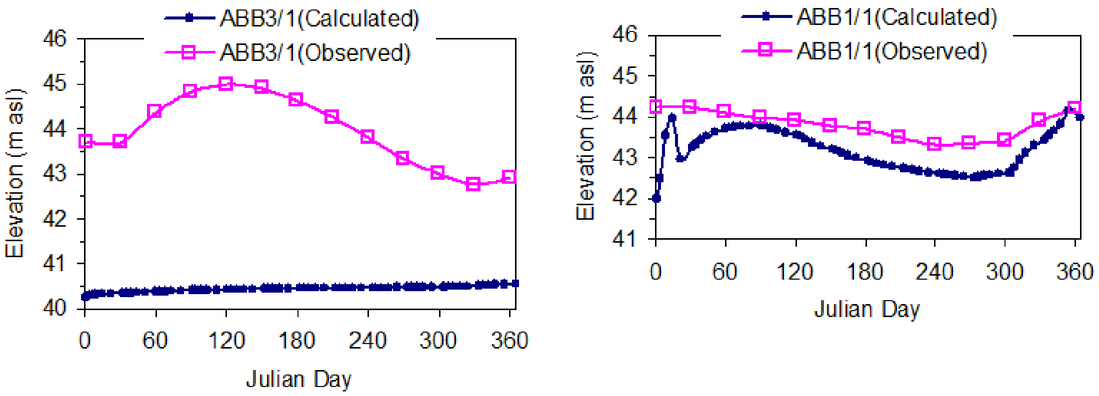


Figure 7-7: Example of transient calibration affected by heterogeneity and initial conditions (data from Abbotsford-Sumas Aquifer, Scibek and Allen, 2005): (a – left panel) poor fit due to aquifer heterogeneity, (b – right panel) reasonable overall fit but with misfit at early times due to wrong initial conditions.

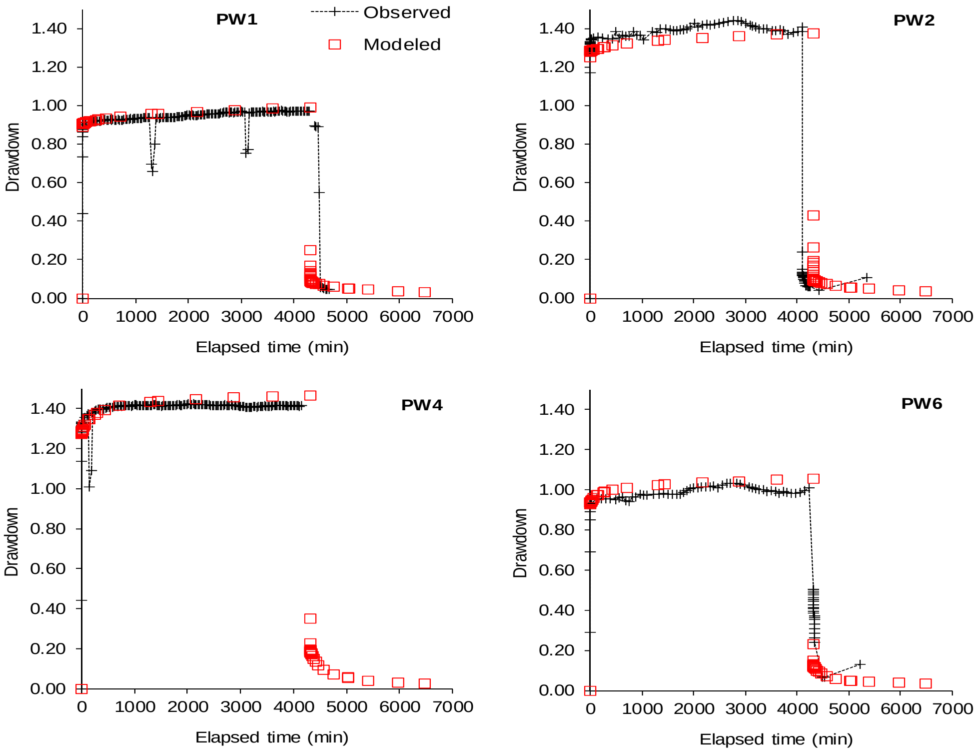


Figure 7-8: Example of transient model calibration using normalized drawdown. Graphs illustrate residuals for transient calibration to pumping tests that have been normalized to initial (static) drawdown, rather than absolute elevation.

7.3.5 Adequacy of Calibration

Subjective judgment of acceptability is based on confirming observations from components of the modelling process, not only the results of model calibration (Woessner and Anderson, 1996). The evaluation of the adequacy of the calibration of a model should be based more on the insight of the modeller and the appropriateness of the conceptual model rather than the exact value of the various measures of goodness of fit. The reviewers should keep in mind that:

- Just because a model is constructed and calibrated, does not ensure that it is an accurate representation of the system.
- The appropriateness of the boundaries and the system conceptualization is frequently more important than achieving the smallest differences between simulated and observed heads and flows (USGS, 2004).

In the hydrogeological modelling practice, a model is commonly considered calibrated when the correlation coefficient is high and the NRMSE is low. There is no one prescriptive numerical criterion for NRMS because each model is different and there are many other considerations than average residual error measure. Generally, NRMSE under 10% is good in many models, and under 5% is very good in terms of average residual fit, however, the following should be taken into consideration:

- A very low NRMSE is not desirable if the model requires unreasonable assumptions and complexity to achieve that result
- The average fit statistic does not take into account the potential bias, the outliers, and the spatial distribution of residuals.
- At high topographic relief sites, a 10% error bound allows the modeller 20-50m error bars on any head calibration point.
- Presentation of absolute errors (in meters) is very useful as a reality check.

Over-calibration occurs when the model parameters are artificially fine-tuned (to minimize calibration residuals) to a higher degree of precision than is warranted by the knowledge or measurability of the physical hydrogeological system. Without performing model verification (see Section 7.4), the artificially low residuals might otherwise be used to overstate the precision of the model's predictions. During model review, the following may indicate over-calibration:

- The presence of many more zones of equal hydraulic properties than is supported by the available geologic and test data. In any calibration method, the choice to set up recharge zonation is made by the modeller based on physical processes and available data.
- Calibrated values are very precise, to within centimetres at a site with large topographic relief.
- The residuals are very small and there are no outliers (the whole model domain is very well calibrated).
- Very low NRMSE is reported without supporting information about spatial and temporal distribution of residuals or distribution of final calibrated parameters.

In theory it would be possible to specify every cell in a model that has an observation associated with it as a specified head cell in the model. This would produce a perfect match between simulated and observed heads. It is conceptually unreasonable to simulate random cells as specified heads that could serve as sources and sinks of water. Thus, although the measures of calibration might make it appear to be a well-calibrated model, in effect the violation of a reasonable conceptual model makes it a poor model.

A model with very small number of calibration targets may suffer from too coarse calibration if the modelling objectives require more detailed model predictions at spatial scale not supported by the data.

Important aspects of the model, such as the conceptualization of the flow system, that influence the appropriateness of the model to address the modelling objectives, are often not considered during calibration by many investigators; instead their focus is on the quantitative measures of goodness of fit. The appropriateness of the conceptualization of the ground-water system and processes should be evaluated during calibration. Thus, the method of calibration, the closeness of fit between the simulated and observed conditions, and the extent to which important aspects of the simulation were considered during the calibration process are all important in evaluating the appropriateness of the model to address the problem objectives.

7.4 MODEL VERIFICATION (MODEL TESTING)

Once the model is calibrated, additional testing of the calibrated model is advised. This process is called model *verification* (Woessner and Anderson, 1996).

7.4.1 Verification Process

The process of verification involves running the calibrated model in predictive mode to check whether the prediction reasonably matches the observations of a reserved data set, deliberately excluded from consideration during calibration.

The resulting degree of correspondence can be taken as an indicator or heuristic measure of the uncertainty inherent in the model's predictions.

If adjustments to parameters or boundary conditions are required to achieve verification, then the calibration simulation needs to be re-run, and re-assessed. This process may need to be repeated until a set of parameters and boundary conditions is identified that produces a good match to both the calibration and verification data sets.

When only one data set is available, it is not advisable to artificially split it into separate "calibration" and "verification" data sets, but it is usually more important to calibrate to data spanning as much of the modeled domain as possible. A data set refers to the entire site data (e.g. heads, fluxes, unit geometries) which are sufficient for good model calibration. A second data set might consist of a second set of measurements (heads, fluxes) taken during some stress test (e.g. large scale pumping test, a new excavation or flooding or existing excavation, etc.).

The confidence in the model's performance as a predictive tool would be enhanced if the verification data set was also from a distinct hydrological period (compared to the prediction data set), consistent with recommendations to address the non-uniqueness issue. Verification of a transient model may also be performed against a set of reserved groundwater level hydrographs during the same calibration period, which were not part of the original calibration. In general the greater the change and the applied stress the stronger the model verification.

7.4.2 Model Verification Benefits

The benefits of model verification include:

- Verification improves confidence in calibrated model by using an independent data set.
- Verification estimates the range of uncertainty associated with model predictions, before the predictions are made.
- Verification, with good calibration, provides a level of predictive accuracy that is consistent with the degree of confidence required to answer the modelling objectives.
- Verification protects against over-calibration.

7.4.3 Examples

Examples of model verification include:

- Calibrate using pump test and predict seasonal behavior

- Two- way pumping test (calibrate one pump test and model second test)
- Observe predicted response in new monitoring wells (drilled after model calibration)
- Compare predicted and observed response over time (e.g. pit dewatering; TSF operation etc.)

A calibrated but unverified model may still be used as a predictive tool, provided a sensitivity analysis is undertaken on the calibration and prediction simulations (see Section 8).

7.5 PROJECT LIFE CALIBRATION

Projects in the natural resource industry have a significant project life often extending over many years to decades. Those projects provide many opportunities to verify, and if required, recalibrate a groundwater model (Figure 7-9). For example, during the early stages of operations when the groundwater system is responding to large new hydraulic stresses such as open pit development and/or start-up of a tailings impoundment, recalibration may be undertaken. The regulatory decisions and requirements for additional reporting or permitting after model re-calibration will be discussed at that time. This process may continue through the operation of the mine and continue to closure and post-closure.

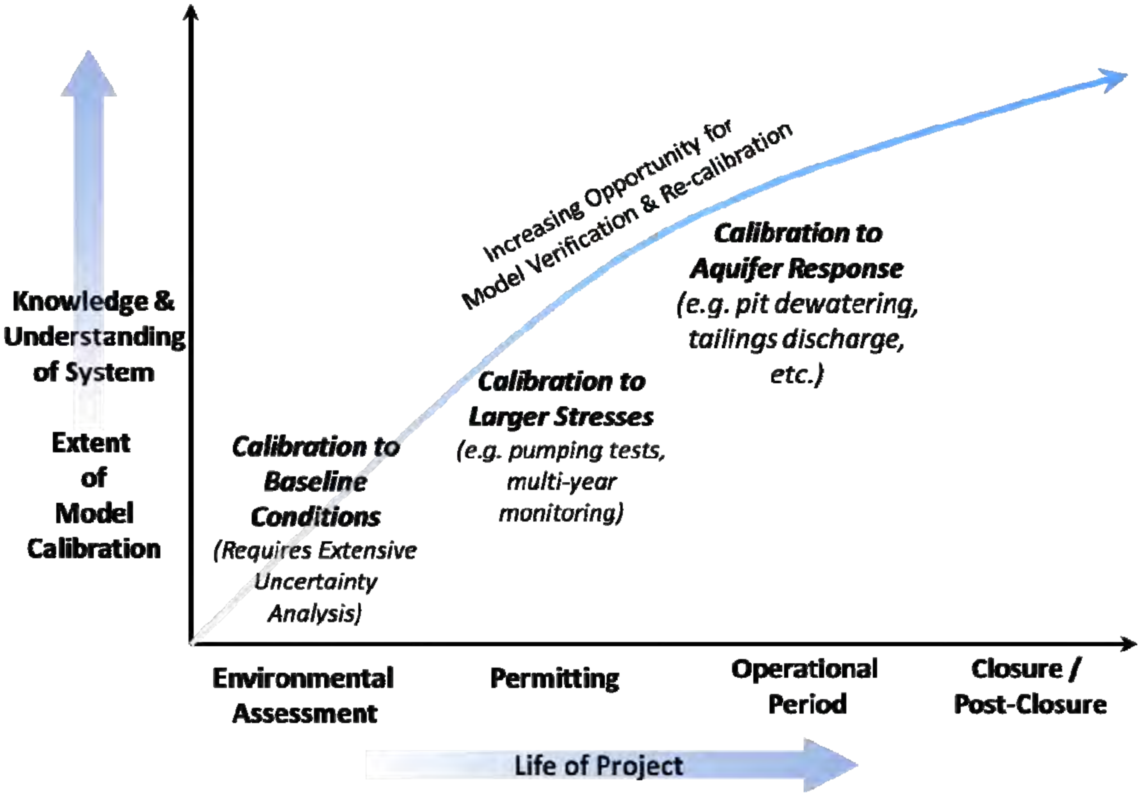


Figure 7-9: Potential for calibration and verification during life of project.

7.6 CASE STUDIES

7.6.1 Case Study 2: Underground Mine

Case Study 2 illustrates the use of multiple calibration models to address uncertainty in the conceptual model. An overview of the project and modelling objectives can be found in Section 3 of the guidelines.

The calibration was carried out in two distinct phases of parallel modelling. Due to uncertainty in the conceptual model, two simulations (Model A and Model B) were carried through the steady state head and flow calibration phases. Both models are based on the hydrogeological units presented in Figure 7-10a. These simulations did not initially include the major fault zone inferred to run through the Site.

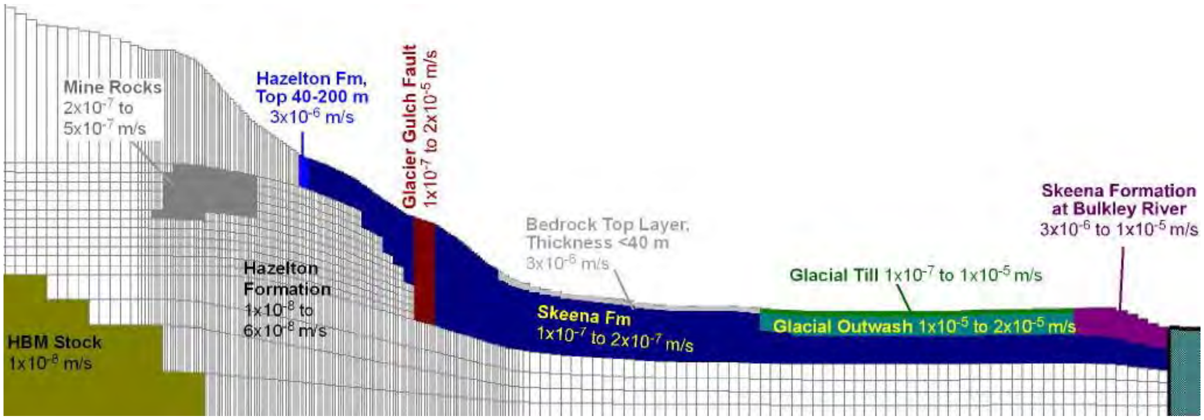
During model setup, uncertainty in the distribution of hydraulic conductivity was recognized as having a potential influence on predictions. To address this uncertainty, multiple conceptual models were calibrated in parallel to assess potential effects on model results. Calibration was completed in an initial phase for two plausible hydraulic conductivity distributions based on the same hydrogeological units. During a second calibration phase, hydrogeological units were modified. The hydrogeological unit distribution and calibration results from the different conceptual models are presented in Figure 7-10a and Table 7-1, respectively.

Calibration results for Model A and Model B show nRMSE of less than 10%, which the modeller judged to be acceptable given the (limited) size of the dataset.

Table 7-1: Calibration results for initial phase

	Hydraulic Conductivity Values (m/s)			
Material	**Calib 1A**		**Calib 1B**	
	Horizontal	Vertical	Horizontal	Vertical
Hazelton Volcanics	$3x10^{-8}$	isotropic	$6x10^{-8}$	isotropic
Skeena Rocks	$2x10^{-7}$	isotropic	$1x10^{-7}$	isotropic
Mine Area Rocks	$5x10^{-7}$	isotropic	$2x10^{-7}$	isotropic
Skeena Rocks at Bulkley River	$3x10^{-6}$	isotropic	$1x10^{-5}$	isotropic
Layer 1 Glacial Till	$1x10^{-5}$	$1x10^{-6}$	$1x10^{-5}$	$1x10^{-6}$
Layer 2-6 Glacial Deposits	$2x10^{-5}$	$1x10^{-6}$	$1x10^{-5}$	$1x10^{-6}$
Calibration Statistics for All Wells				
nRMSE	6.0%		5.6%	
Residual Mean (m)	1.4		7.5	
Calibration Statistics for Site Wells Only (DAV-1A, DAV-03, DAV-04, 700 Adit Pressure)				
nRMSE	11.0%		7.1%	
Residual Mean (m)	-9.4		-3.8	
Predicted Outflow at 1066 Adit (L/s)	16		11	

(a) Hydrogeologic units for first phase of calibration



(b) Hydrogeological units for second phase of calibration (change is the relatively higher hydraulic conductivity and size in the “granodiorite” unit, and constraints on hydraulic conductivity for other units.

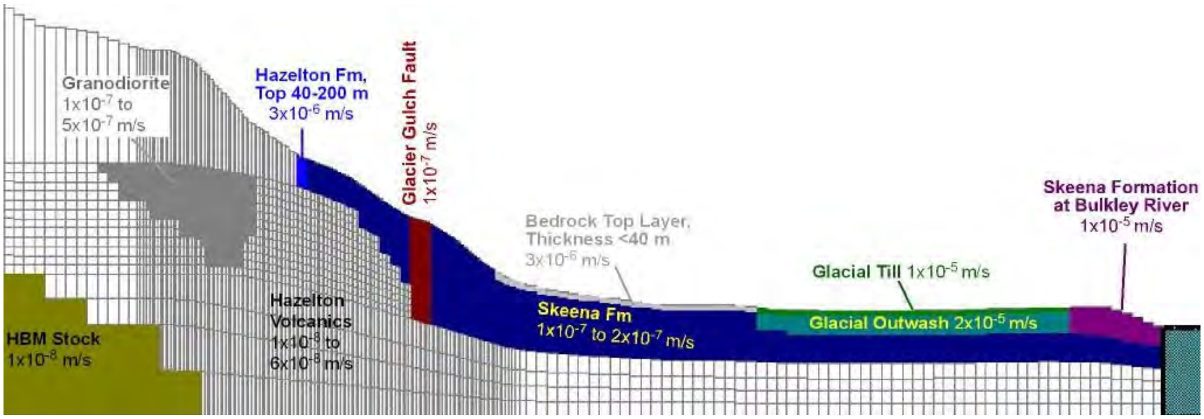


Figure 7-10: Distribution of hydrogeologic units for Case Study 2 calibration phases

In addition to Model A and Model B of the First Calibration stage, a Second Calibration phase involved the inclusion of a new hydrogeological unit in the mine area to represent a zone of (relatively) higher hydraulic conductivity. The distribution of hydrogeological units of this third model is presented in Figure 7-10b. Furthermore, the rate of sub-glacial recharge was increased in order to assess model sensitivity to this parameter. Again, the calibration targets were achieved for this conceptual model (see Figure 7-11).

Table 7-2 presents the different model results for the various calibrated models. It is seen that the second conceptual model (which includes higher K zones) predicts higher inflows to the underground workings. This example illustrates the non-uniqueness of model calibration. Three different conceptual models could be calibrated with equally good calibration statistics.

Table 7-2: Comparison of model results for Case Study 2 conceptual models and calibrations.

Discharge Zone	Calib 1A	Calib 1B	Calib 2
Peak Modeled 700 Adit Flow	35	29	42
Flow at end of Adit Development	25	27	29
Mine Flow 5-d into Mine Operation	51	43	47
End of Mine Life Flow	21	22	26

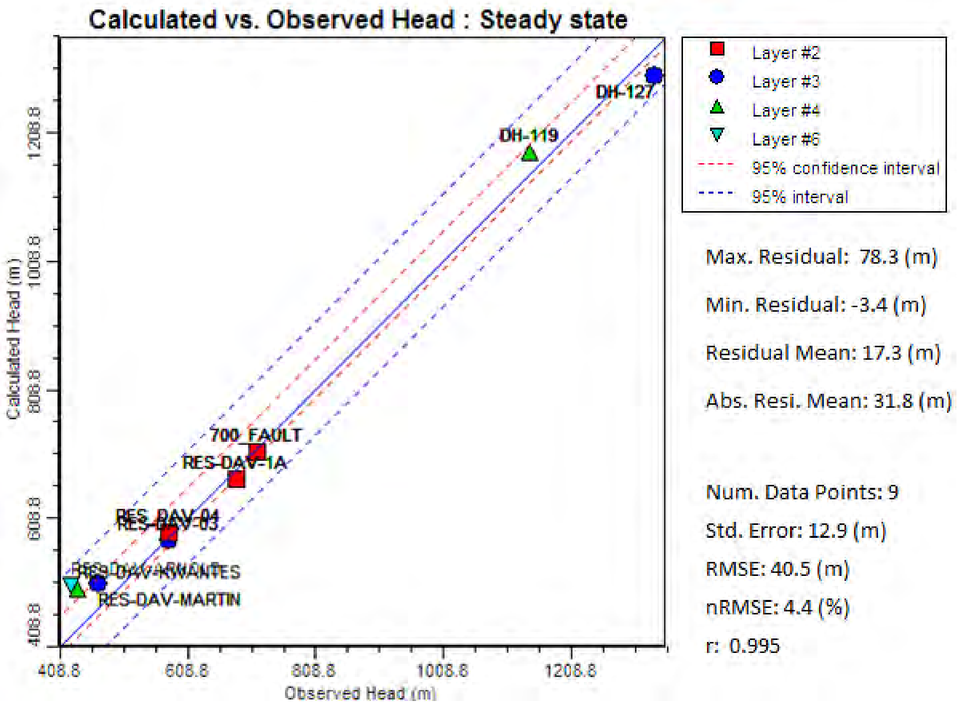


Figure 7-11: Scatterplot of calibration results for Second Calibration model, Case Study 2

7.6.2 Case Study 3: Groundwater Extraction Project

Case Study 3 illustrates the use of both steady-state and transient calibration. For groundwater extraction projects, pumping tests will be expected. Models developed to assess these projects benefit from the ability to have calibration not only to aquifer-wide hydraulic heads (ideally) but also the transient aquifer response to the pumping test. These calibration phases allowed calibration to both hydraulic conductivity and storage parameters.

In Case Study 3, an initial, steady-state baseline model was calibrated to observed head values from across the model domain. Calibration residuals were presented in scatterplot form (Figure 7-12).

Following this, the model was calibrated transiently to a pumping test conducted on one of the pumping wells. Transient calibration results were presented as time series and are illustrated in Figure 7-13. This calibration allowed better constraint of specific storage and specific yield, in the area affected by the pumping test.

Additional, aquifer-wide transient calibration was then completed by applying the storage parameters from the pumping test calibration to the entire aquifer and applying seasonal recharge rates for different time periods.

Results from this last transient calibration period were presented graphically, as maps showing both observed and modeled water levels for two discrete periods (October and January). Figure 7-14 shows the water table calibration map for the October period.

By using steady-state and transient calibrations, confidence in model predictions is improved. For groundwater extraction studies, in which the water balance for the entire aquifer is of importance, transient calibration to both pumping tests and seasonal water level fluctuations is important. Calibration only to the pumping test data would not necessarily provide confidence that other important factors, such as seasonal recharge, were appropriately evaluated.

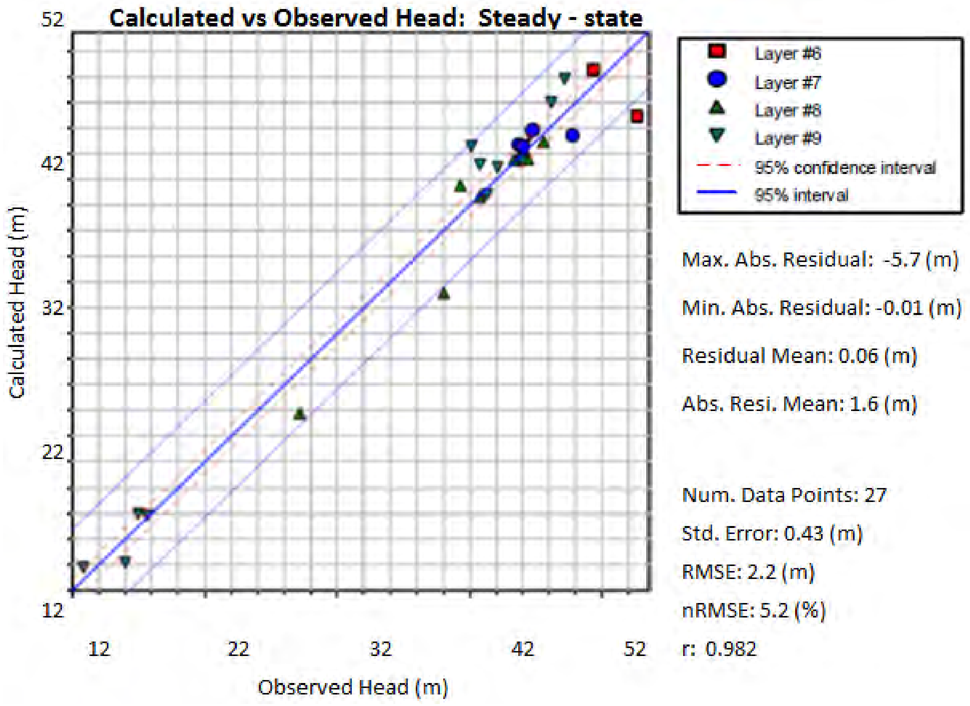


Figure 7-12: Scatterplot of steady-state calibration residuals for Case Study 3

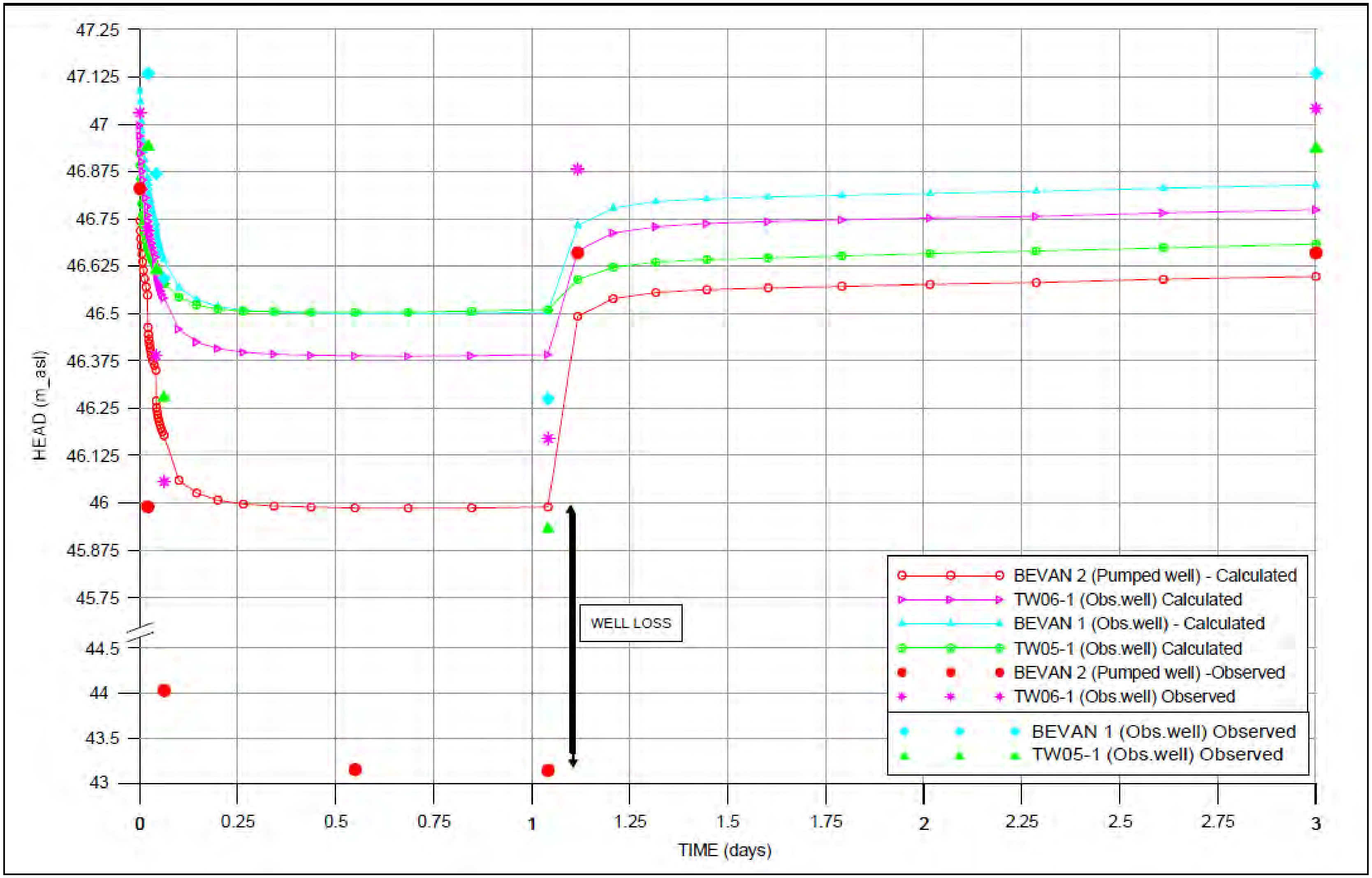
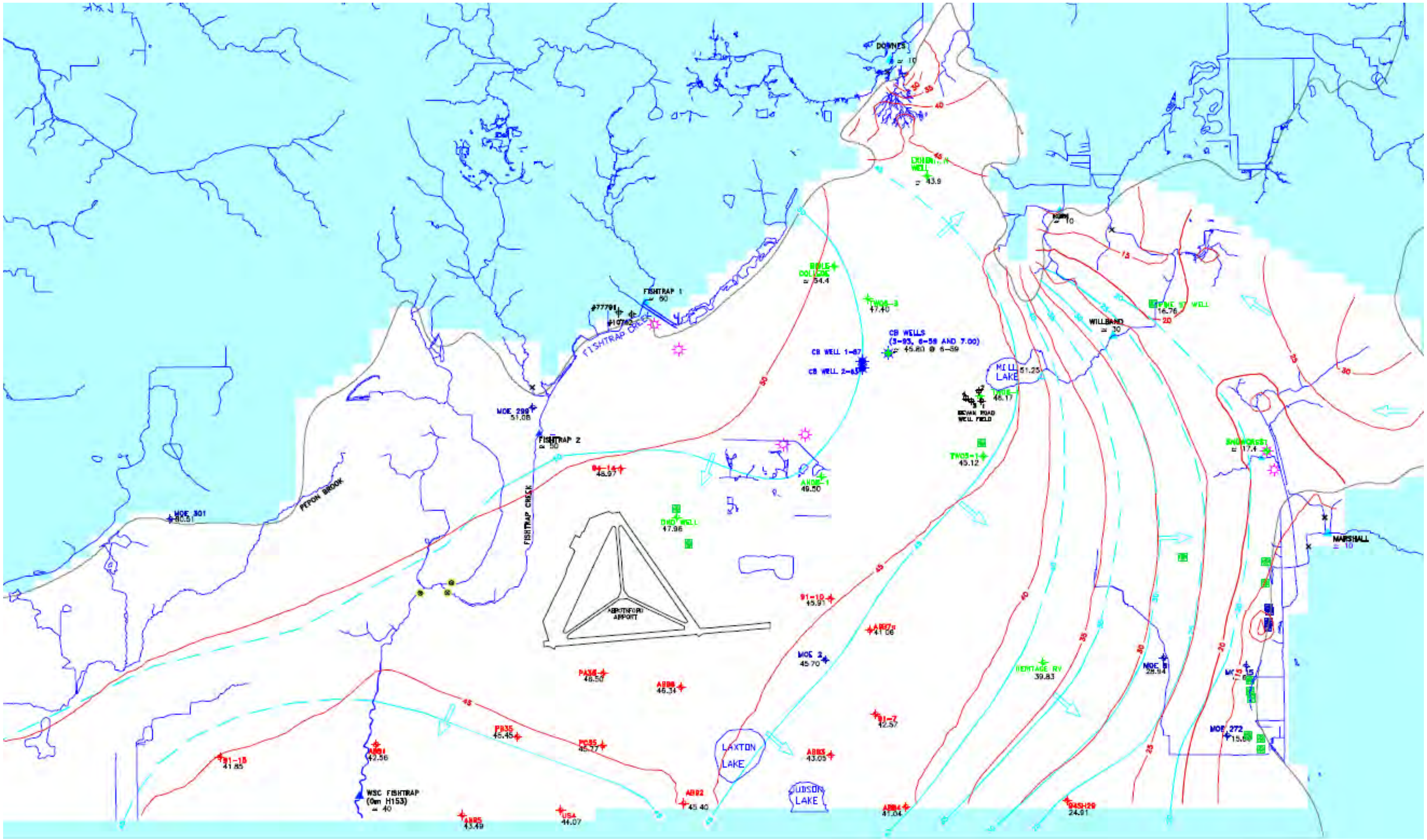


Figure 7-13: Results of transient calibration to pumping test data for Case Study 3.



Note: Blue lines = observed; red lines = simulated

Figure 7-14: Water table calibration map for Case Study 3 seasonal transient model

SUMMARY POINTS FOR MODEL CALIBRATION & VERIFICATION

1. Model calibration is an iterative process of refining the numerical model's representation of the hydrogeological system to achieve a desired degree of correspondence between the calculated values (model simulation) and observations of the groundwater flow system.
2. Alternative conceptual models should be discussed and/or calibrated if there is large uncertainty in the choice of one.
3. The observed data used as calibration targets must have sufficient spatial distribution for all models, and sufficient temporal distribution for transient models. A large number of uniformly distributed calibration targets will increase the likelihood of obtaining a unique calibration.
4. The error bounds and calibration targets should be set before the calibration process. Sources of error in each calibration point should be assessed and quantified to assign relative weights to data points before starting calibration.
5. Calibration of a numerical model may be done by manual trial and error or by automatic parameter estimation methods, or a combination of the two. Manual trial-and-error calibration gives the modeller significant insight into the factors controlling the system and should always be part of model calibration.
6. The use of automated parameter estimation techniques requires significant specialized experience by the modeller. If not used properly, this method may yield incorrect results or no result at all.
7. Non-uniqueness arises because many different sets of model input parameters can produce nearly identical model outputs. Non-uniqueness cannot be eliminated but it may be reduced by restricting parameter ranges to observed ranges, and to use groundwater flux observations or ranges to constrain the solution.
8. Calibration residuals are the basic quantitative measures of goodness of fit, and their distribution in space and in relation to model features and boundaries is very important. In general, the residual should be a small fraction of the difference between the highest and lowest heads across the site, but acceptable residuals depend on site-specific model setup.
9. Graphical model error plots such as scatterplots of residuals are very important in describing the model goodness of fit of individual calibration targets (usually hydraulic heads). It is very important to display the spatial distribution of residuals from calibration.
10. Transient calibration can provide improved confidence in model results, particularly in cases where seasonal effects may be important.
11. Subjective judgment of acceptability is based on confirming observations from components of the modelling process, not only the results of model calibration. The insight of the modeller and the appropriateness of the conceptual model are more important than the exact value of the various measures of goodness of fit. Just because a model is constructed and calibrated, does not ensure that it is an accurate representation of the system.
12. Verification reduces uncertainty of model predictions. Projects in the natural resource industry have a significant project life often extending over many years to decades. Those projects provide many opportunities to verify, and if required, recalibrate a groundwater model.

8 MODEL PREDICTION & UNCERTAINTY

8.1 INTRODUCTION

The focus of previous sections has been on the conceptualization, development and calibration of the baseline models, which include a conceptual and mathematical model of current conditions or existing conditions as they exist at the time of modeling. This section advances the discussion to the use of predictive models, which are an attempt to quantify the performance of a future field system in response to project implementation.

8.2 PREDICTIVE MODELLING IN THE MINING CONTEXT

As noted in detail in Section 3, predictive groundwater modeling in mining and resource project development is undertaken for one or more of the following reasons:

- Quantify project impacts
- Evaluate engineering designs
- Assess the need for mitigation measures.

Examples of mining impacts that may necessitate predictive groundwater modeling include (See Section 3 for further details):

- Quantify inflow to the open pit or underground workings.
- Estimate the aquifer drawdown & loss of groundwater discharge (to surface water) as a result of a mining operation such as pumping to dewater the area of an open pit.
- Evaluate the potential for groundwater mounding as a result of increased seepage from tailings impoundments or waste rock dumps.
- Quantify seepage & associated contaminant transport from mine waste disposal facilities.

This section does not repeat or further discuss the many examples of predictive groundwater modeling in the mining context discussed in Section 3. The reader is referred to Section 3 for background and context.

8.3 THE BASICS OF PREDICTIVE MODELLING

8.3.1 General

A conceptual model of future conditions, as they are reasonably likely to be once planned construction and/or development is implemented at the mine or resource development project, should be formulated using guidelines provided in preceding sections of this document.

Model predictions are the outputs from the predictive model. As such, model predictions quantify possible or potential future conditions that cannot be observed today. Hence a predictive model cannot be calibrated to these new conditions prior to project implementation. It can only be calibrated to present or past observed conditions.

As the project proceeds and verification is undertaken as previously described, however, the output from the predictive model may be compared to monitored conditions and the model calibrated or verified.

8.3.2 The Baseline Model

These guidelines recommend that predictive modeling be preceded by the preparation of a calibrated baseline model. The baseline model is a replication of current conditions. If current conditions are not sufficiently defined to compile a calibrated baseline model, any predictive model will be uncertain and have limited value in risk assessment and practical decision making.

8.3.3 The Predictive Model

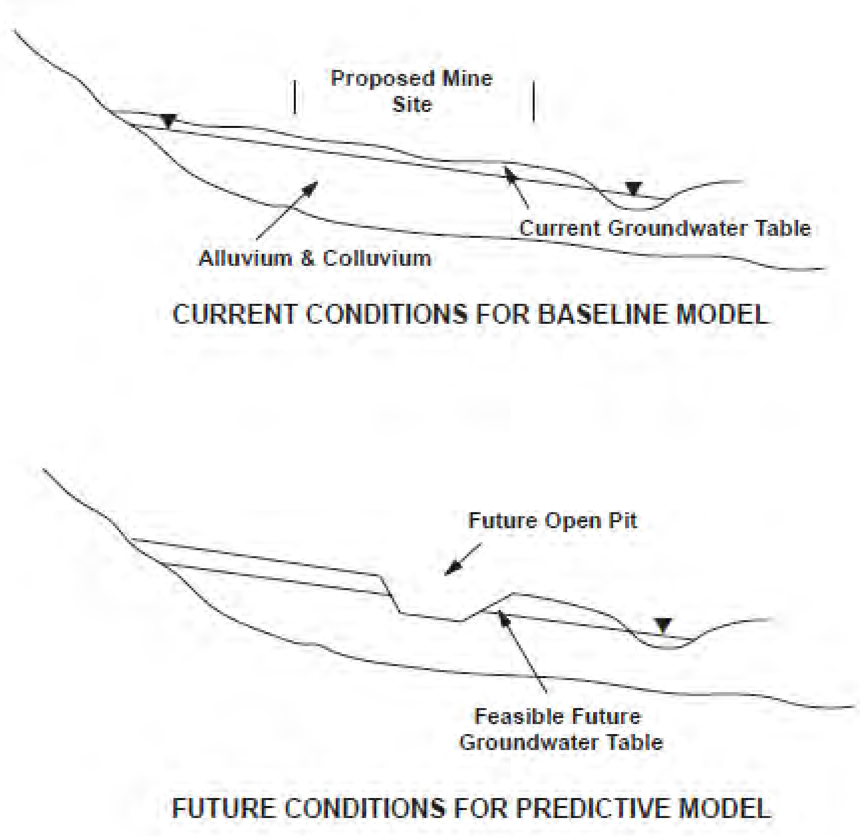
The predictive model is based on and derived from the baseline model. In formulating the predictive model, changes are made to the layout and details of the baseline model to reflect the changes that are planned as part of project implementation.

For example, the baseline model (Figure 8-1) may represent the current conditions of a site where groundwater is recharged from hills upgradient of the proposed mine site, the groundwater table is some meters beneath the surface of the site, and the groundwater flows on to a downgradient river. Project implementation is proposed to include an open pit excavated to below the current groundwater level. Pit dewatering is proposed to lower the level of the water table and to deal with inflow to the pit. This is the situation modeled with the predictive model.

In this example, changes will need to be made to the baseline grid layout and boundary conditions. Once these changes are made, the modified model may be run (predictive simulations undertaken) in order to predict the position of the water table in the presence of the open pit and to estimate inflow from the groundwater to the pit.

Note that in this particular example, many different simulations may be undertaken to model the impact of the pit as it gets bigger and deeper. In addition to adjusting the predictive model to reflect the changing pit geometry, it may also be necessary to adjust the parameters that quantify strata potentially affected by the open pit advance. For example, excavation of an open pit may reduce the stress on the surrounding rock, induce stress relief, and hence an opening of the rock joints that control permeability – the result could be a significant increase in the hydraulic conductivity of the bedrock surrounding the open pit. This would have a major impact on groundwater flow.

In this example, changes have will need to be made to the baseline grid layout and boundary conditions. Once these changes are made, the predictive modified model may be run (predictive simulations undertaken) in order to predict the position of the water table in the presence of the open pit and to estimate inflow from the groundwater to the pit.



CURRENT CONDITIONS FOR BASELINE MODEL

FUTURE CONDITIONS FOR PREDICTIVE MODEL

Figure 8-1: Baseline vs. Predictive Conceptual Groundwater Models

8.3.4 The Limited Extent Predictive Model

If the baseline conceptual model includes the project site and surrounding region, it may not be necessary to incorporate so large an area in the predictive model. Indeed more than one predictive model may be formulated and used to quantify the performance of specific project works. For example, as shown in Figure 8-2, it may be appropriate to include in the predictive model of the proposed open pit only the immediately surrounding area likely to be affected by pit excavation. Or it may be appropriate to include in the predictive model of the tailings impoundment only the immediate upgradient and downgradient area.

As shown in Figure 8-2, more than one limited-extent predictive model may be formulated to analyze the performance of a mine facility as it develops or grows over the many years of mining. For example, the open pit may be so shallow for the first five or so years of mining that it is unlikely to impact or affect groundwater. By the end of the life of the mine, however, the pit may have been excavated to a depth where the pit induces a fall of the groundwater table. And after mine closure, the pit may fill up with water and thereby increase infiltration to the immediately surrounding zone causing a rise of the groundwater table.

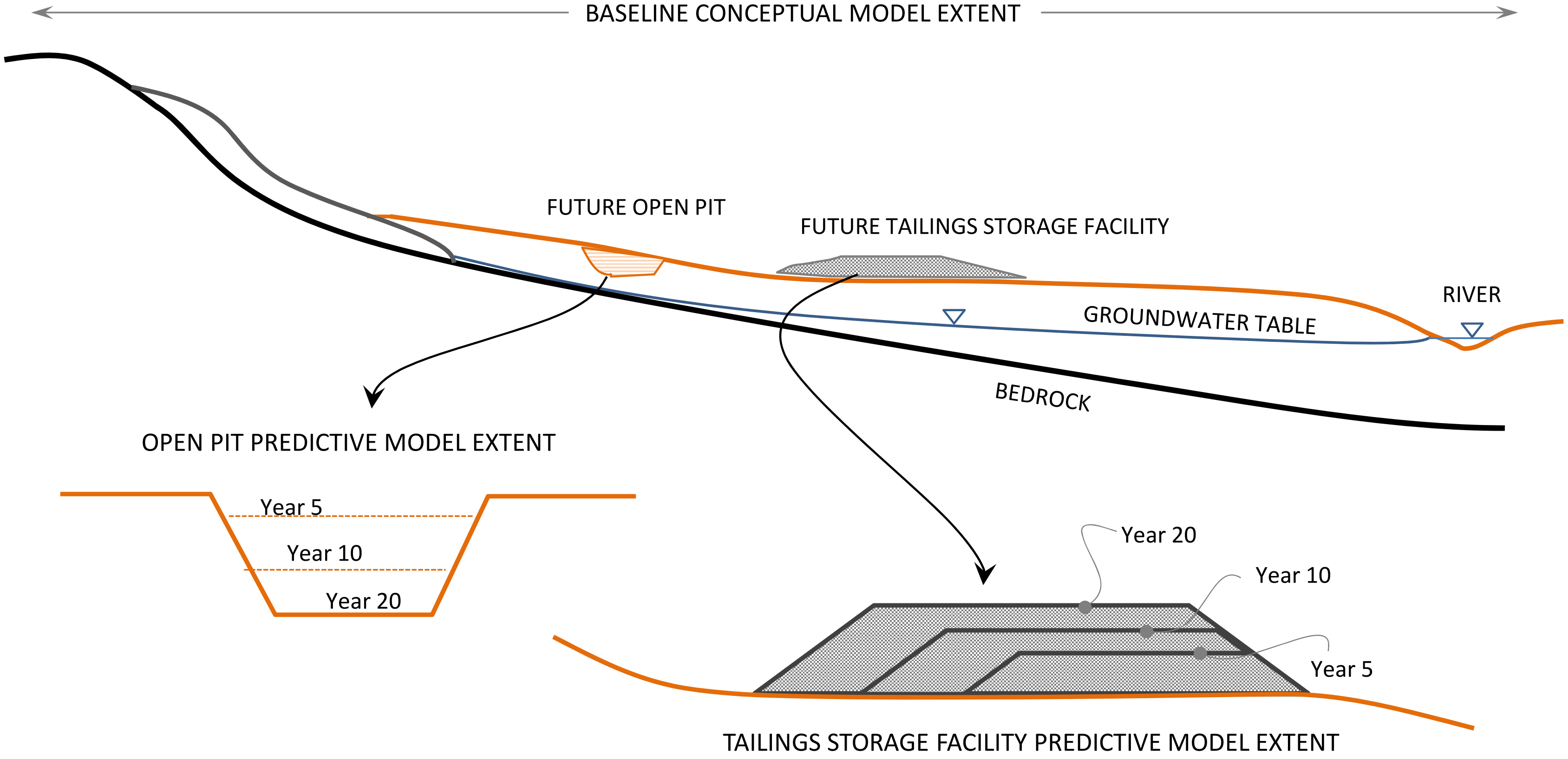


Figure 8-2: Scales of model extent for baseline and predictive models

8.3.5 Scoping Simulations

Scoping simulations are model runs completed without prior calibration of the baseline model or in the absence of a baseline model.

These guidelines recognize that in some circumstances a fully calibrated baseline model may not be feasible. Reasons for this may include:

- The site is inaccessible.
- Sufficient field data are not available to calibrate a baseline model.
- There may not have been sufficient time to fully model baseline conditions.
- Rapid decisions have to be made about engineering details.

These guidelines recognize that in such situations, scoping simulations may be the only possible and practical way to advance a project.

In undertaking scoping simulations to model defined future scenarios, the proponent should develop future scenarios in consultation with the regulatory body. The proponent and reviewers should recognize and acknowledge that the model results may be preliminary and may indicate a need to undertake further work to prepare a calibrated baseline model.

It is feasible that a scoping study may indicate reason for optimism – the project may not entail undesirable impacts – and hence the proponent and regulator may concur that the project may proceed subject to conservative provisions including monitoring and the ability to construct mitigation works if the monitoring indicates a need for mitigation measures.

Figure 8-3 shows the results of simple scoping simulations undertaken for an actual site to evaluate the potential impact of a waste rock dump on the elevation of the pre-mining groundwater table. About all that was known was that the upper soils were of low permeability and hence of low strength. These soils would have to be stripped to provide a bedrock foundation strong enough to ensure stability of the slopes of the advancing rock dump. It was known that the low permeability soils inhibited infiltration to the underlying rocks. It was feared that the higher permeability waste rock might act to increase infiltration to the bedrock, thereby raising the groundwater table.

Scoping level predictive modeling confirmed that this could happen and in fact that the water table could rise above current ground level and enter the waste rock. As the waste rock was predicted to be acid generating, such excess water entering and seeping along the lower part of the dump would have given rise to unacceptable acid rock drainage. As a result of this simple scoping study, alternative approaches were implemented.

8.3.6 Prediction Period

Prediction periods at natural resource extraction sites may be as long as the life of the project and for some time after closure. In some cases, it may be necessary to predict conditions for what is now referred to in mining as “in perpetuity”. In such a case, the predictive modeller may choose to define a steady-state condition that represents reasonable and feasible future conditions. Then the modeller may elect to undertake additional simulations to model a range of feasible, but extreme future conditions, including increasing average precipitation or increasing dry climatic influences. The concepts of uncertainty analyses and sensitivity analyses are discussed further in Section 8.6.

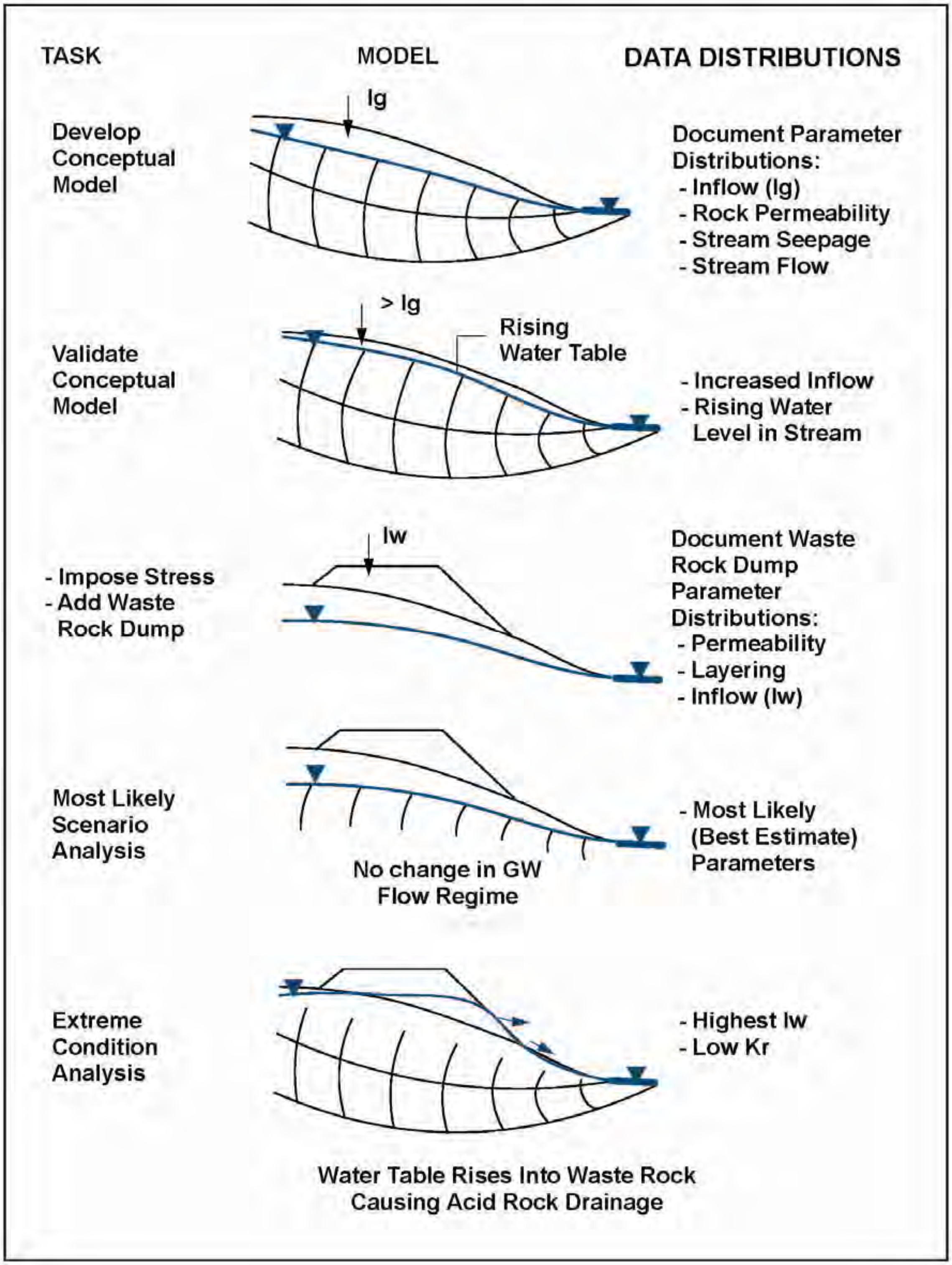


Figure 8-3: Example of scoping simulations for assessing the impact of a waste rock pile on the pre-mining groundwater table

8.3.7 Predictive Modeling for EA Applications

Figure 8-1 illustrates the approach for predictive modelling in the context of an EA application. The first step in predictive modeling is a conceptualization (and definition) of future scenarios that could change the groundwater flow field and/or contaminant transport. If there is uncertainty about these future conditions (e.g. uncertainty in mine plan, uncertainty in seepage rates and/or contaminant concentrations) different future conditions (typically called “scenarios”) should be defined and simulated.

Next, the calibrated baseline model will have to be adjusted to reflect the future conditions to be simulated. This typically requires adjustment to both the conceptual and the mathematical baseline model. Any changes to the conceptual and/or mathematical baseline model should be justified and documented in the modeling report.

Once the predictive model has been constructed the model can be used to predict future conditions. In the context of an EA, the predictive model is typically used to predict the influence of mine development on a VEC. For example, the groundwater model may be used to predict a potential decrease in river flow (due to seepage to a nearby mine) or the potential increase in CoCs in a sensitive creek near a tailings facility.

Any prediction of future groundwater conditions carries some uncertainty and this uncertainty will have to be evaluated as part of predictive modeling. This uncertainty may be evaluated using a deterministic approach (Section 8.4) or using a probabilistic approach (Section 8.5). Either way, predictive modeling should include a range of predictive runs that bracket the uncertainty in model predictions due to uncertainty in the baseline model and uncertainty in future conditions (see Section 8.6 for more details).

In the context of an EA, the model predictions are used to evaluate whether the proposed development has an environmental impact (e.g. loss in river base flow or contaminant concentration in local creek). These predicted system responses are usually compared to a performance criterion, or threshold, for example a minimum stream base flow or water quality guidelines/objectives.

If the predicted system performance is acceptable (i.e. meets the performance criterion) then the predictive modeling is completed. A monitoring plan may be formulated and implemented to assess the validity of the model predictions, if and when the project is implemented.

However, if the predictive system performance is not acceptable (e.g. water quality objectives are exceeded), then the following additional modeling steps are usually required (Figure 8-4):

- Collect additional data (to reduce model uncertainty), update conceptual baseline model, recalibrate model and repeat predictive modeling, and/or
- Design mitigation options (to reduce impact), update predictive model, and repeat predictive modeling.

More guidance on the assessment of model uncertainty in predictive modeling in the context of the EA process is provided in Section 8.6.

8.3.8 Mitigation of Predicted Outcomes

If one or more of the deterministic predictive runs indicate an unacceptable outcome, i.e., there is a reasonable probability that a threshold will be exceeded, mitigation may be required (Figure 8-4)

In the mining context, these are examples of feasible mitigative measures that may be undertaken to ameliorate predicted performance of a mine facility that it is likely or is feasible to lead to an exceedance of regulatory limits:

- Engineered structures to prevent or slow down groundwater flow or isolate some groundwater zone (e.g. dams, cut-off walls, grout curtains, freezing of ground, permeable surround).
- Engineered solutions to change boundary conditions (diversions of surface water, ground covers to limit recharge).
- Active and passive dewatering systems to modify flow and position of water table (dewatering system design, drains).
- Change in natural resource extraction plans and designs (e.g. depth of excavation, schedule, location of dump or excavation).
- Water treatment (water treatment plant, remediation in situ, pumping and discharge elsewhere – pipelines, etc.).

It may be necessary to formulate and run a new or revised predictive model to evaluate the performance of proposed mitigative measures (Figure 8-4).

8.3.9 Monitoring of Model Predictions

The groundwater modeling results should be used to assist in developing a groundwater monitoring program for the project. In setting up the project groundwater monitoring program (Figure 8-4), both the baseline and predictive models must be considered. Specifically, the groundwater monitoring program should provide for monitoring of key parameters, values of which are predicted by the models. Thus measured values may, in the future, be compared to predicted values.

If there is reasonable correspondence between predicted and measured values, confidence in the modelling may be established.

If there is significant deviation between predicted and measured values, it may be necessary to redefine the concepts incorporated into the models, adjust boundary conditions, make runs with alternative parameter values, or otherwise seek reasons for the deviations. If the measured values indicate unacceptable performance, then it may be necessary to implement remedial, corrective, or mitigative measures.

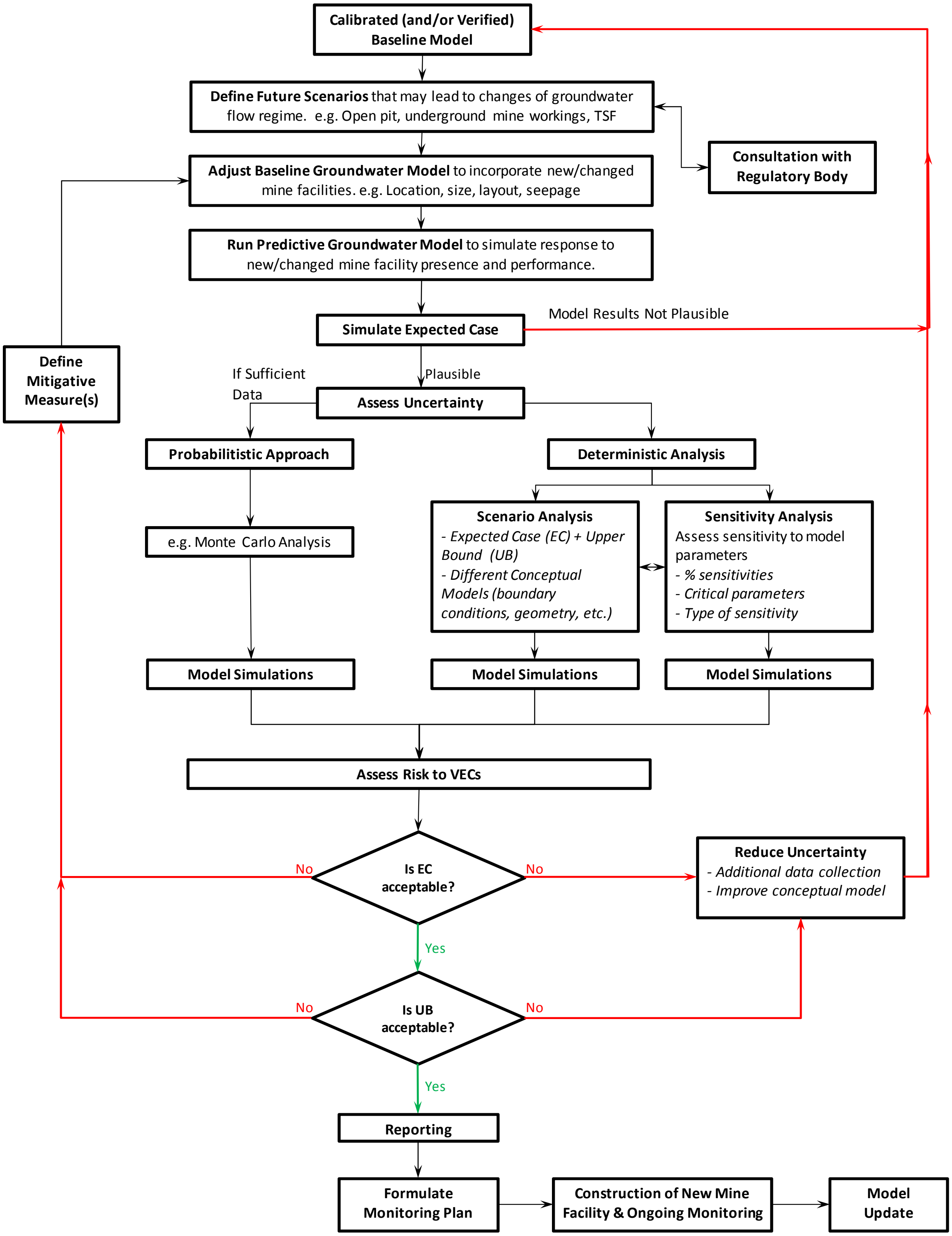


Figure 8-4: Approach to predictive modelling in support of an EA application for a natural resource project.

8.4 DETERMINISTIC PREDICTIVE MODELLING

8.4.1 Background

There are two types on predictive modelling, namely deterministic and probabilistic. This section discusses deterministic modelling. It is recognized that deterministic modelling is by far the most common approach used in the mining industry. This is because deterministic modelling is technically easier to do and is cost effective.

Probabilistic modelling is favored by researchers and those with time and significant data. It is relatively transparent and quantifies the probability of various outcomes. It is not, however, commonly used for routine modelling in the mining industry.

8.4.2 The Link between Deterministic and Probabilistic Modelling

The link between deterministic and probabilistic modelling is illustrated in Figure 8-5.

Basically as illustrated in Figure 8-4, deterministic predictive modelling involves the use of a limited number of discrete scenarios identified subjectively by the modeler and run to quantify potential outcomes. Conversely probabilistic predictive modelling involves the uses of statistical and probabilistic methods to compile a probability distribution function (“PDF”) of outcomes.

As noted in Figure 8-5, the deterministic runs fall somewhere on the probability curve of possible outcomes, although it is generally not possible to be specific about where exactly they fall.

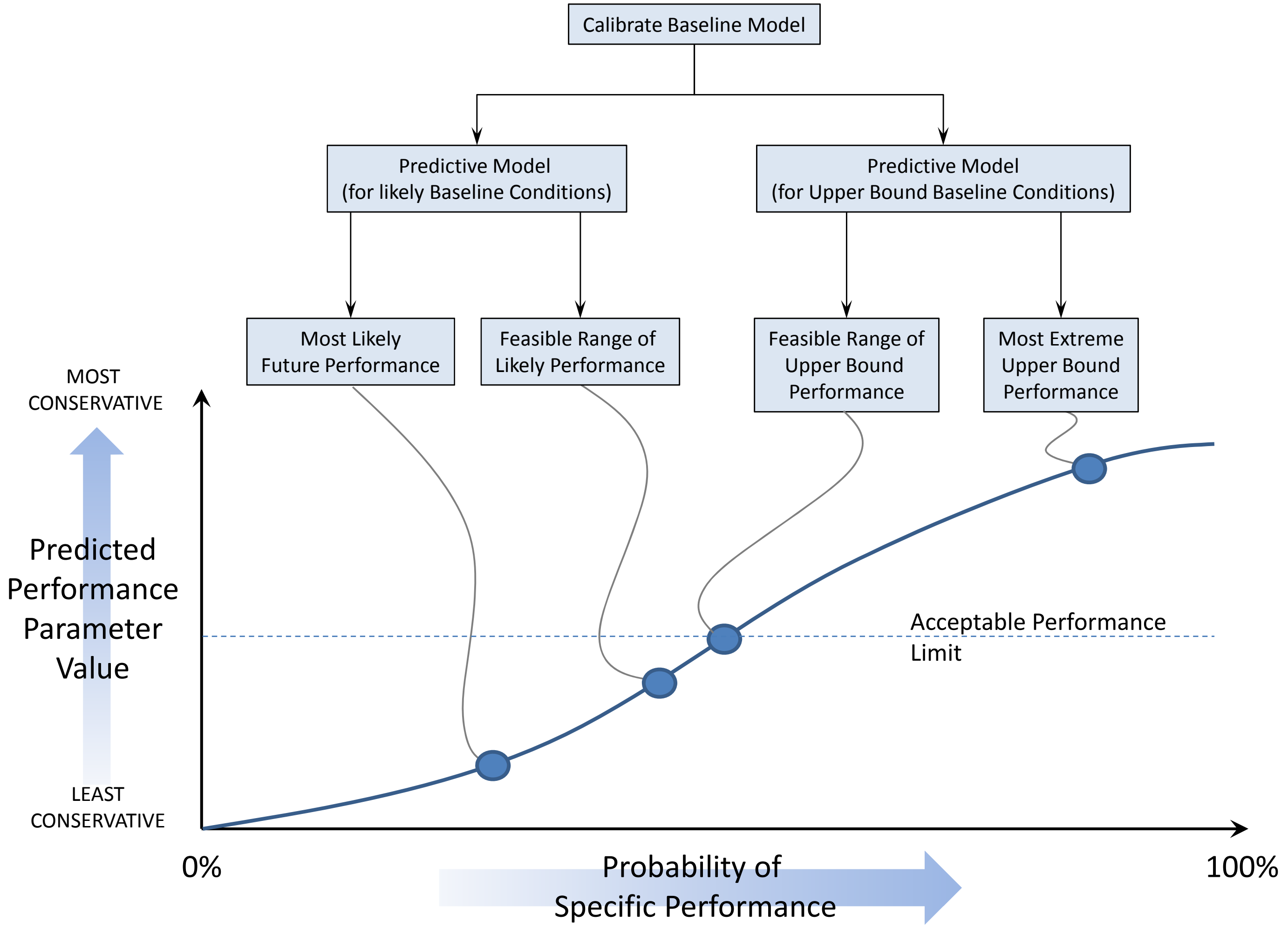


Figure 8-5: Carrying uncertainty from the baseline model(s) to the predictive model(s) for projects of significant potential impacts

8.4.3 The Essence of Deterministic Modelling

Deterministic modeling involves a description of a parameter or a process with uniquely defined qualities. A deterministic parameter has, or is assumed to have, a unique value or a unique spatial distribution. The outcome of a deterministic process is known with certainty. There is, or is assumed to be, a clear cause-and-effect relation between independent and dependent variables.

In the deterministic approach, parameter uncertainty is described using the base-case condition bounded by extreme cases (upper and lower bound models as defined below). The range of model output parameters and/or conditions is bracketed by the upper and lower bond models. The likelihood of various results is not quantified.

8.4.4 Types of Deterministic Models

The following are the most commonly used types of deterministic models used in the mining industry. The specifics of each model type are defined by the modeller on the basis of subjective judgment.

8.4.4.1 Expected Case Models

In these guidelines, the term expected case (EC) is used to refer to a working hypothesis or model that in essence reflects the most likely field conditions.

The expected case should not be confused with the baseline model described above. Not the least of the differences is that there should be both an EC baseline model and an EC predictive model.

The EC model incorporates the most probable conditions based on at least the general nature, pattern, and properties of the system being modeled.

The EC model can be viewed as the model that seeks to replicate the most reasonable conditions that may be expected or anticipated. Some refer to the model as the average condition or base-case model. Whatever way the expected case model is referred to, it should be recognized that it incorporates a certain degree of optimism, for it generally does not represent less favorable conditions which may be encountered in the field. It is not a conservative approach.

8.4.4.2 Upper Bound Models

In these guidelines, the term upper bound (UB) model is used to refer to the baseline or predictive model that incorporates the most unfavorable conditions compatible with the available data about the system being modeled. In the context of an EA, the unfavourable always represents the scenario with the greater environmental impact. The UB model should be formulated to be realistically conservative.

8.4.4.3 Lower Bound Models

In these guidelines, the term lower bound (LB) model is used to refer to the baseline or predictive model that incorporates the most favorable conditions compatible with the available data about the system being modeled.

8.4.4.4 The Worst Case Model

The upper bound model is not the worst case scenario, although some mistakenly confuse the two. The upper bound model incorporates the most unfavorable conditions compatible with data. The worst case model uses very high or very low parameter values, what-if-conditions, and the most extreme values conceivable – even though there are no data to support the likelihood of such extreme values occurring. The worst case model may be considered to be extremely or even unrealistically conservative.

8.4.5 Guideline Recommendations

These guidelines recommend that for groundwater models submitted by a proponent to the regulator, the following scenarios should be considered and documented (see Figure 8-4):

- Expected case baseline model
- Expected case predictive model
- Upper bound baseline model
- Upper bound predictive model.

Depending on the specifics of the project, particularly the potential for detrimental impact, the proponent should consider running the predictive model in both the expected case and upper bound mode using the upper bound baseline model as the foundation of the predictive model.

The worst case model need not be run as a matter of routine modelling and reporting. It may be done only for specific cases where there is considerable concern about worst case potential impacts (e.g. the potential presence of a fault that has hitherto not been proven to exist). And when it is done, these guidelines recommend that it be accompanied by statistical data, if available, that quantify the low to very low probability of occurrence. In most cases it is very difficult to quantify the probability of a worst case scenario model, but some input parameters (e.g. rainfall events of certain magnitude, hydraulic conductivity distribution) may be assigned probabilities of exceedance for a specified value.

8.5 PROBABILISTIC PREDICTIVE MODELLING

8.5.1 Overview

In probabilistic analyses, parameter uncertainty is described using frequency distributions and statistics. Standard statistical techniques are used to predict a likelihood (statistical probability) of possible outcomes. The probabilistic approach has the following benefits relative to the deterministic approach:

- Captures available information about uncertainty
- Provides the range of possible outcomes and the probability associated with each outcome
- Identifies the most important parameters which cause most of the uncertainty.

8.5.2 Monte Carlo Simulation

Monte Carlo Simulation is the most rigorous approach to probabilistic predictive modelling in the mining context. It involves running a large number of simulations of either or both the baseline and a predictive model. For each run or simulation, a value of the parameter or parameters of interest is selected at random from the known or assumed underlying distribution. Thus for one of the many runs, some parameters may be the average of the parameter distribution while other parameters may be at the extremes of the parameter distribution.

By making many runs each with a random assignment of parameter values from the parameters' distributions, it is possible to plot the resulting distribution of outcomes. This is generally considered to be the most comprehensive way to model and quantify complex systems involving many varying parameters.

8.5.3 Guideline Recommendation

With the increasing power of groundwater modelling computer codes, it is anticipated that Monte Carlo Simulation in groundwater modelling will become more commonly used in groundwater impact assessment.

Thus these guidelines recommend that for large projects in very sensitive environments, high risk to VECs and/or project subjected to considerable scrutiny and public concern, the proponent consider undertaking Monte Carlo Simulations as a way to enhance project understanding and to quantify uncertainty.

If Monte Carlo simulations are considered, data collection requirements will be significantly higher than for typical deterministic approaches. Care must also be taken to avoid over-simplification of parameter distributions. It is typical that parameters such as hydraulic conductivity can be highly variable over large spatial scales, particularly when dealing with fractured bedrock. Incorrect assumptions about probability distributions may negate the benefit of using a probabilistic approach in the first place, or shift focus from the extremes, which are uncertain but of greatest concern, to averages which may be better understood, but less likely to be a problem.

Probabilistic modeling is not recommended for projects where the available field data (e.g. hydraulic testing data) does not adequately describe the parameter distributions (e.g. parameter distribution function of hydraulic conductivity of important aquifer units).

8.6 SENSITIVITY ANALYSIS OF PREDICTIVE MODELLING

8.6.1 General

Sensitivity is the variation in the value of one of more output variables (such as hydraulic heads) or quantities calculated from the output variables (such as groundwater flow rates) due to changes in the value of one or more inputs to a groundwater flow model (such as hydraulic properties or boundary conditions).

Sensitivity analysis is a procedure for quantifying the response of a model’s output to an incremental variation in a model parameters, stresses, and boundary conditions.

This section discusses sensitivity in predictive groundwater modeling. Specifically this subsection focuses on the sensitivity analysis procedure which involves a systematic variation of model input values to:

- Identify those model input elements that cause the most significant variations in model output (list of ranked sensitivity coefficients, etc.), and to
- Quantitatively evaluate the impact of parameter variability (sometimes referred to as parameter uncertainty) in model input on the degree of calibration and on the model's predictive capability (calculate the effect of parameter change on the quantitative and qualitative calibration criteria).

8.6.2 Linking Baseline and Predictive Model Sensitivity

In compiling the baseline model, as described in preceding sections, sensitivity analyses will have been undertaken. Thus the modeler should have a reasonable understanding of which parameters most affect simulation outcomes.

In undertaking predictive modeling, as described here, the modeler should undertake additional sensitivity analyses. The scope of the sensitivity analyses will depend on the modeling objectives and, in the context of an EA, on the risk to VECs. In general, the scope of sensitivity analyses will increase with the complexity of the project and the risk to VECs.

Predictive modeling involves the use of a calibrated baseline model suitably adjusted to formulate a predictive model and hence to quantify future performance of the system being studied. In addition, predictive modeling may be undertaken to establish the relevance and importance of the sensitivity measure of a parameter.

It is recommended that in evaluating the joint impact of the sensitivity of a baseline model to one or more specific parameters and the sensitivity of the predictive model to the same parameters, both the sensitivity of the baseline model calibration and the sensitivity of the model prediction should be quantified (ASTM D 5611). The following are guidelines for undertaking such a study:

- For each different value of each parameter of the sensitivity analysis, run model simulations for both the calibration scenario (calibrated base case) and the predictive scenario (future conditions).
- Determine the type of sensitivity (Table 8-1) for each parameter determined based on whether the change in calibration is significant and whether the change in prediction is significant (see Figure 8-6 for numerical examples of the sensitivity types listed in Table 8-1 and further discussed below.)

Table 8-1: Four Sensitivity Types (after Brown, 1996)

Change of Predicted Parameter		**CHANGE IN CALIBRATION**	
	(effect)	Insignificant	Significant
CHANGE IN PREDICTION RESULTS	Insignificant	**Type I**	**Type II**
	Significant	**Type IV**	**Type III**

By way of further explanation of this table and the implications of each type of sensitivity, note:

- **Type I**: There is an insignificant effect for both model calibration residuals and predictive model results (relative to modeling objectives). In other words, within a reasonable range of values the parameter is varied but nothing significant happens as a result. This parameter type does not need further data collection or monitoring.
- **Type II**: There is a significant effect on model calibration, BUT an insignificant effect on predictive model results (relative to modeling objectives). The model calibration is affected (residuals increase for some part of the parameter range being tested) so the parameter has an effect on calibration goodness of fit. However, the results of predictive model are still insensitive to this parameter.
- **Type III**: There is a significant effect on both model calibration and model prediction results (relative to modeling objectives). The parameter has an effect on calibration goodness of fit and a corresponding effect on predictive model results.
- **Type IV**: There is an insignificant effect on model calibration, but a significant effect on predictive model results (relative to modeling objectives). The model calibration is not affected and does not help constrain this parameter value, while the results of predictive model are sensitive to this parameter.

Types I and II are of no concern because the impact on predictions is insignificant. Type III is of concern only for an uncalibrated model, and a proper calibration of this parameter is the solution. The sensitivity is important but it is known and can be avoided by model calibration.

Type IV is a cause for concern because non-uniqueness in a model input might allow a range of valid calibrations, but the choice of value significantly impacts model prediction. It is important to determine the actual value of this parameter and not rely on model calibration to estimate this parameter. It should be measured with good data (model field audit), and ideally the data should represent the same stresses as in the predictive model simulations.

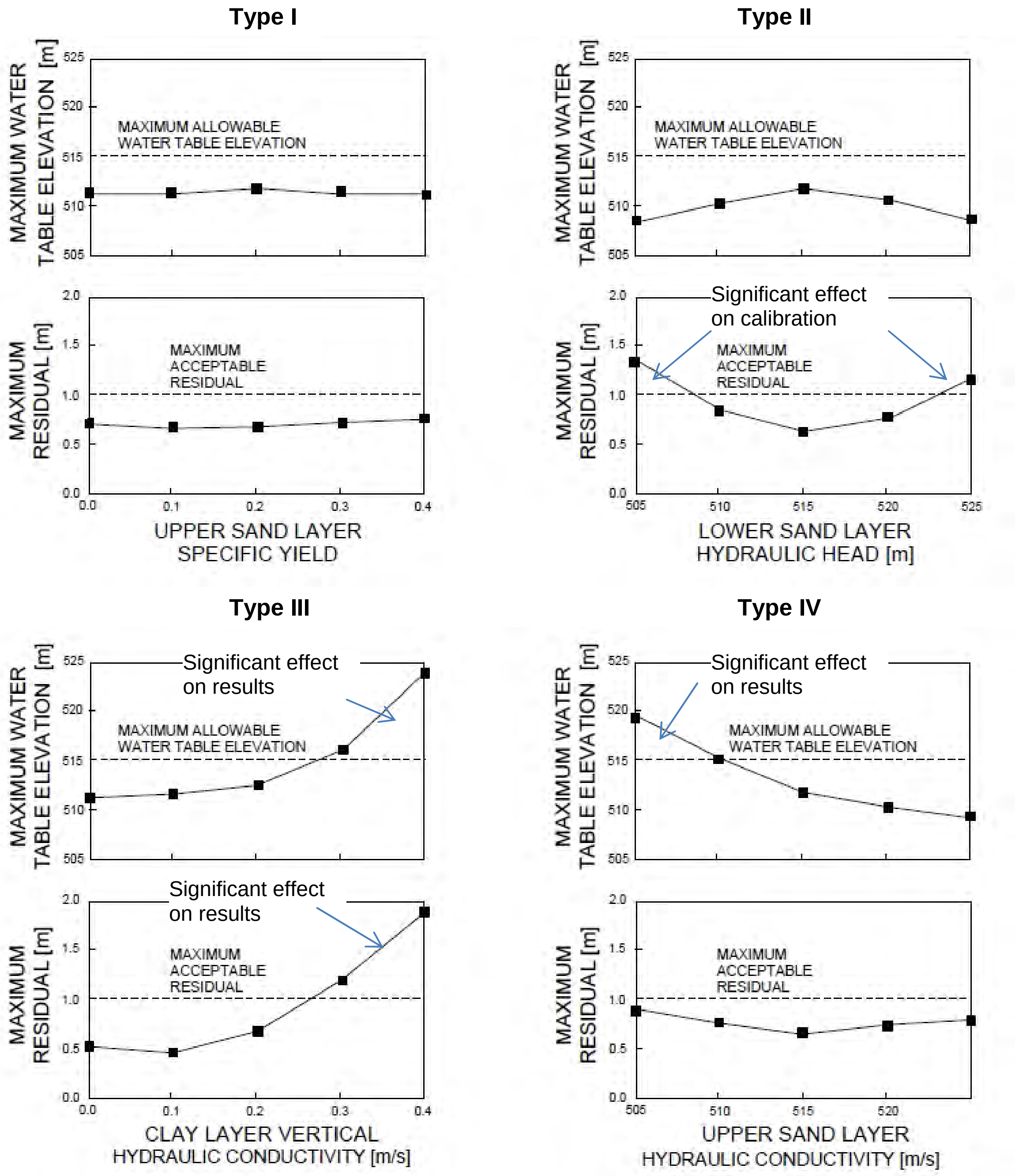


Figure 8-6: Numerical examples of sensitivity types (from Brown, 1996)

8.7 UNCERTAINTY IN PREDICTIVE MODELLING

8.7.1 General Concepts

In previous sections of these guidelines (Figures 2-2 and 3-1 and associated text) it is noted that after the predictive runs have been done, that the modeler conduct uncertainty analysis. Accordingly, this subsection discusses uncertainty analysis in the context of predictive modelling.

Uncertainty is the absence of confidence or assuredness that a groundwater modelling condition or parameter has a definite, ascertainable, or fixed value. In general, the uncertainty in groundwater modelling may result from:

- Subjective uncertainty due to imperfect knowledge or ignorance of a complex system (simplification of the system) or process uncertainty.
- Stochastic uncertainty due to randomness (small scale heterogeneity, future changes, etc.) of parameters.

In the context of these guidelines, the terms “model uncertainty” and “uncertainty analysis” are used in the more general colloquial context. Uncertainty analysis in the strict definition of the word is an advancing field of statistical evaluation which is not discussed further in these guidelines.

8.7.2 Sources of Uncertainty

The calibrated baseline model may be used as the basis of a predictive model that is run in order to predict and assess how the groundwater system might change in response to postulated changes in hydrological stresses, model boundaries, or parameters (e.g. inflow in response to pit excavation).

The most common sources of uncertainty in a baseline model include:

- Uncertainty in the conceptual model (missing key element or process)
- Uncertainty in model calibration (non-uniqueness).

Uncertainty due to errors in measurements (e.g. water levels used as calibration targets; hydraulic conductivity values used to develop conceptual models) is usually relatively small compared to the potential errors in conceptual modeling and/or model calibration.

In addition to uncertainty in the baseline model there will always be uncertainty in the predictive model. An evaluation of uncertainty in model predictions is an important aspect of predictive modeling and should always be documented.

Simulations completed with the predictive model usually carry a greater uncertainty than simulations using the baseline model. In most cases, the predictive model carries most, if not all, of the uncertainties of the baseline model. In addition, the predictive model carries uncertainties unique to predictions of future conditions, including:

- The stresses to be simulated using predictive models are usually very different from the stresses used for calibration of the baseline model (e.g. the model is calibrated to seasonal fluctuations while the predictive model is used to predict pit dewatering);
- The future conditions to be simulated are often not very well understood (e.g. uncertainty in future mine plan; uncertainty in quantity and/or quality of future seepage);

- Future hydrogeological conditions may change (e.g. future use of aquifer by other users; influence of future climate change).

These guidelines recommend that the uncertainty in model predictions be evaluated using a range of future scenarios in combination with sensitivity analyses (see below).

8.7.3 Guidelines

These guidelines call for the documentation of modelling uncertainty as the word is used in the more general colloquial context. These guidelines do not call for the use of advanced Uncertainty Analysis as a part of predictive modelling.

These guidelines recommend documented peer review by the proponent and by the regulator (if deemed necessary and appropriate) of groundwater models as a way to limit the possibility of there being significant uncertainty arising from subjective factors.

These guidelines recommend that error-based uncertainty be limited by implementation of Quality Assurance and Quality Control programs and procedures.

The following recommendations are provided for an assessment of the uncertainty in model predictions in the context of an EA application (see Figure 8-4):

- Model predictions should be completed and presented for the EC and the UB using either a deterministic and/or probabilistic approach;
- For projects with significant risk to VECs AND significant uncertainty in the conceptual model, alternative conceptual models should be developed and used for predictive modeling
- Sensitivity analyses should be completed and presented to assess the uncertainty in model calibration (non-uniqueness)
- Additional sensitivity analyses should be completed and documented to assess the uncertainty in future conditions (e.g. different source terms, different mine plans, change in recharge due to climate change).

8.8 CASE STUDY

8.8.1 *Case Study 2 – Underground Mine*

For an overview of this Case Study and details regarding development of the groundwater flow and transport model, refer to Appendix C.

In order to address the high level of uncertainty resulting from a very limited dataset and low confidence in the model conceptualization, two different models (A and B), slightly different in concept, were used to provide a range of estimates of discharge over the mine life (Figure 8-7).

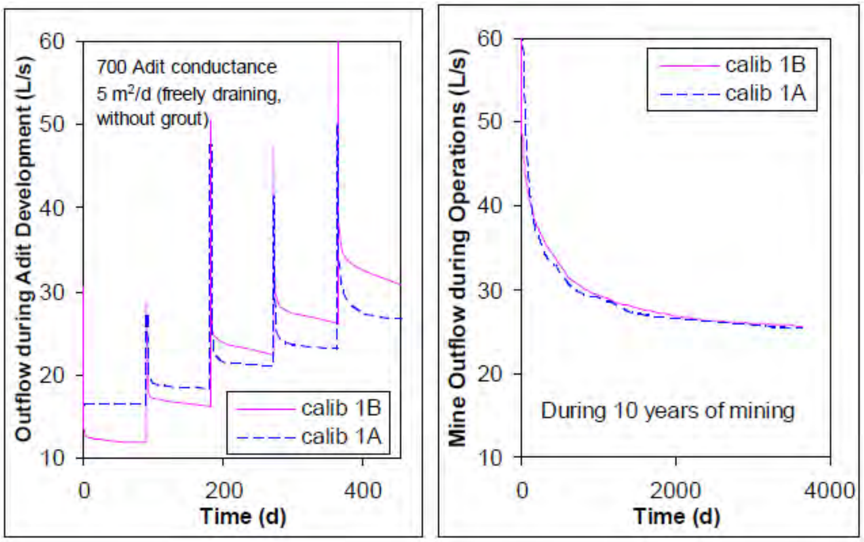


Figure 8-7: Discharge estimates for adit construction and mine operation.

As Model B provided higher estimates of discharge (more conservative), it was selected for a sensitivity analysis of drain conductance. Drain conductance in this model represents, in effect, the efficacy of grouting employed to prevent seepage into the underground workings. This is effectively an operational parameter that may be adjusted during construction. A higher drain conductance in the simulation represents a less effective grout, while a low conductance would represent a grout that precludes seepage into the workings. Figure 8-8 presents the results of this sensitivity analysis.

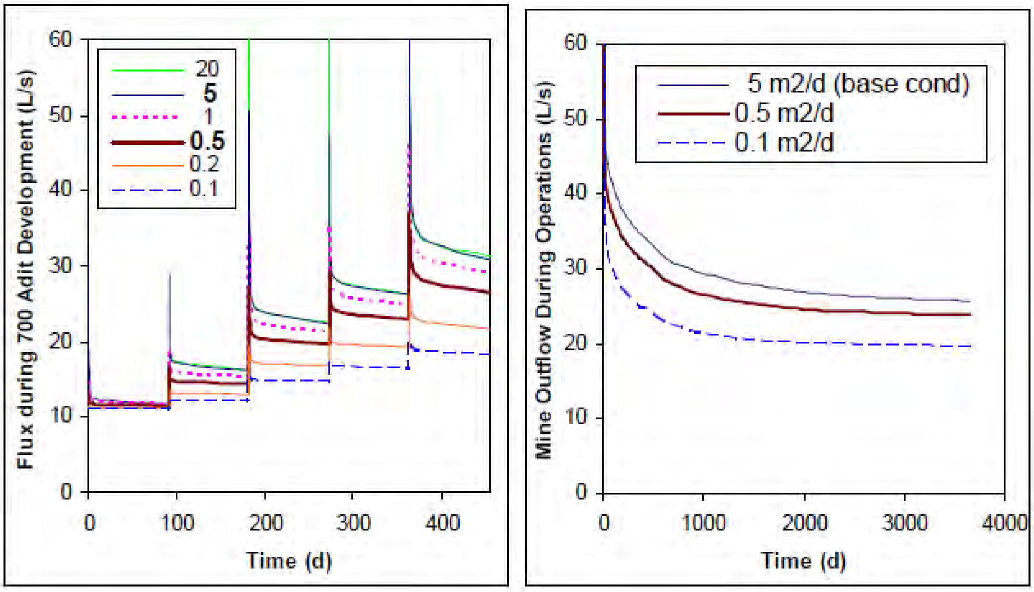


Figure 8-8: Sensitivity analysis of simulated drain conductance

An additional model scenario (i.e. conceptual model) was developed and simulated which assumed the presence of a prominent fault structure through the Site. Inclusion of the fault zone in the model only slightly reduced discharge to the mine workings by effectively lowering the water table in the mine area. The only scenario that would result in increased discharge to the mine is a highly transmissive fault that effectively connects the underground workings to the area of sub-glacial recharge west of the mine. However, this scenario was predicted to increase discharge to the mine workings only slightly.

Further sensitivity analyses were undertaken to evaluate the effect of hydraulic conductivity perturbations on the solution. The hydraulic conductivity values assigned to each hydrogeologic unit were systematically varied to assess which have the greatest impact on mine discharge values. Through this process, it was determined that the model was most sensitive to the rock unit that hosts the mine workings.

Additionally, the model sensitivity to recharge was studied. Sub-glacial recharge west of the mine was shown to significantly influence discharge estimates.

The use of different model scenarios and sensitivity runs, an upper bound estimate of mine discharge was estimated. This estimate represents the most reasonably conservative scenario under the range of simulated conditions.

This approach represents the recommended modelling strategy for identifying and quantifying model sensitivity and uncertainty. Nevertheless, this modelling effort would have significantly benefited from a more robust dataset for model conceptualization and initial calibration.

SUMMARY POINTS FOR MODEL PREDICTION AND UNCERTAINTY

1. These guidelines recommend that predictive modelling be preceded by the preparation of a calibrated baseline model. If current conditions are not sufficiently defined to compile a calibrated baseline model, any predictive model will be uncertain and have limited value in environmental assessments and practical decision making.
2. If undertaking simple scoping simulations to model defined future scenarios, the proponent should develop future scenarios in consultation with the regulatory body. The proponent and reviewers should recognize and acknowledge that the model results may be preliminary and may indicate a need to undertake further work to prepare a calibrated baseline model.
3. Any prediction of future groundwater conditions carries some uncertainty and this uncertainty will have to be evaluated as part of predictive modeling. This uncertainty may be evaluated using a deterministic approach or using a probabilistic approach.
4. These guidelines recommend that the uncertainty in model predictions be evaluated using a range of future scenarios in combination with sensitivity analyses. Sensitivity analyses should be completed and presented to assess the uncertainty in model calibration (non-uniqueness) and additional sensitivity analyses should be completed and documented to assess the uncertainty in future conditions.
5. These guidelines recommend that both Expected Case and Upper Bound conditions be considered and documented for both the baseline and predictive model. Depending on the specifics of the project, particularly the potential for detrimental impact, the proponent should consider running the predictive model in both the expected case and upper bound mode using the upper bound baseline model as the foundation of the predictive model.
6. For projects with significant risk to VECs AND significant uncertainty in the conceptual model, alternative conceptual models should be developed and used for predictive modeling
7. For large projects in very sensitive environments, high risk to VECs and/or project subjected to considerable scrutiny and public concern, the proponent should consider undertaking Monte Carlo Simulations as a way to enhance project understanding and to quantify uncertainty. Probabilistic modeling is not recommended for projects where the available field data does not adequately describe the parameter distributions.
8. If predicted outcomes exceed acceptable limits (i.e. in terms of environmental criteria or stakeholder tolerance) it may be necessary to formulate and run a new or revised predictive model to evaluate the performance of proposed mitigative measures.
9. The groundwater modeling results should be used to assist in developing a groundwater monitoring program for the project. In setting up the project groundwater monitoring program, both the baseline and predictive models should be considered.

9 TRANSPORT MODELLING

9.1 INTRODUCTION

A solute transport model describes the movement of solutes dissolved in groundwater. Solutes dissolved in groundwater may include major ions (e.g. calcium or sulphate), metals (e.g. iron, copper, cadmium) and miscible organic constituents (e.g. BTEX, LEPH). In the context of environmental assessments, “solutes” are also referred to as “contaminant of concern (CoC)” or simply “contaminants”.

In these guidelines the term “solute” is used in the general discussion of “solute transport” and the term “CoC” is used in the context of solute transport modeling for environmental assessments (also referred to as “contaminant transport”). The use of the terms “contaminant” or “contaminant transport” in these guidelines does not necessarily imply a demonstrated impact (or risk of impact) to the environment.

This section will provide an overview of the concepts of solute transport modelling and provide guidance on its application to natural resource projects.

9.2 CONCEPTS OF SOLUTE TRANSPORT MODELLING

Solute transport in groundwater is controlled by physical and geochemical mass transport processes (e.g. Domenico and Schwartz, 1990).

All solutes are influenced by the same physical transport processes, namely advection and dispersion. In contrast, geochemical transport parameters depend on the solute of interest as well as geochemical conditions in the aquifer. Solutes which are not influenced by geochemical transport processes are defined as “non-reactive” or “conservative” solutes and can be simulated using a “conservative” solute transport model.

Solutes which are influenced by chemical transport processes are defined as “reactive” solutes and require the use of a “reactive” solute transport model.

9.3 PHYSICAL TRANSPORT PROCESSES

9.3.1 Advection

Advection describes the movement of groundwater under a hydraulic or pressure gradient. Advective transport describes the movement of dissolved solutes carried along with flowing groundwater. The direction and rate of advective transport coincide with that of the groundwater flow (Domenico and Schwartz, 1990).

The rate of advective transport is described by a modified version of Darcy’s Law:

$v = Ki/n$

where
v = average linear velocity of water movement (in L/T)
K = hydraulic conductivity (in L/T),
i = hydraulic gradient (L/L) and
n = effective porosity (L^3/L^3)

In words, the average linear velocity (or simply “transport velocity”) is directly proportional to the hydraulic conductivity and the hydraulic gradient and inversely proportional to the effective porosity. The above transport equation is very useful in estimating travel time of groundwater and/or solutes dissolved in groundwater.

The effective porosity of an unconsolidated homogeneous material may be as high as its total porosity. However, most aquifers contain dead-end fissures, unconnected pore-space and lower permeability than average material, and therefore the effective porosity of such materials is generally lower than their total porosity (NGCLC, 2001).

In highly fractured aquifers, the effective porosity may be as high as the porosity of the fractures. In dual porosity aquifers (i.e. fractured porous materials), the relevant porosity may be somewhere between that of the fissure and matrix porosity and may change with average flow velocity (NGCLC, 2001).

Advective transport can be simulated very efficiently using particle tracking codes (see Section 5.2.5). Particle tracking codes can be used to determine the flow path (“path-line”) and the average travel time of a solute. An analysis of advective transport (using particle tracking) should always be carried out prior to considering other transport processes using a full solute transport model (see Section 5.2.5).

9.3.2 Dispersion

As water and solutes migrate through the subsurface via advection, they will tend to spread out, parallel to and normal to the flow path. The result will be dilution of the solute by a process known as dispersion. The mixing that is known along the streamline of fluid flow is called longitudinal dispersion. Dispersion which occurs normal to the pathway is called lateral (or transverse) dispersion (Fetter, 2001).

Dispersion occurs at the pore-scale and at the macroscopic (field) scale.

9.3.2.1 Mechanical Dispersion

Longitudinal dispersion at the pore scale is caused by the following factors (see Figure 9-1a):

- Pore size - some pores are larger than others and allow fluid to move faster;
- Path length - some particles travel along longer flow paths to go the same linear distance;
- Friction in pores - fluid moves faster through the center of pores than along the edges.

Lateral dispersion is caused by the fact that as a fluid containing a solute flows through a porous medium, the flow paths can split and branch out to the side (or in the vertical) (see Figure 9-1b). This lateral spreading will occur even in the laminar flow conditions that are prevalent in groundwater flow (Fetter, 2001).

The mechanical dispersion caused by the factors described above is equal to the product of the average linear velocity and a factor called the dynamic dispersivity (α_L). The dynamic dispersivity has units of length and is a function of the subsurface material (porous medium or fractured bedrock). At the field scale, the dispersivity is also influenced by the heterogeneity of the aquifer unit and is therefore scale-dependent (see Section 9.3.2.3).

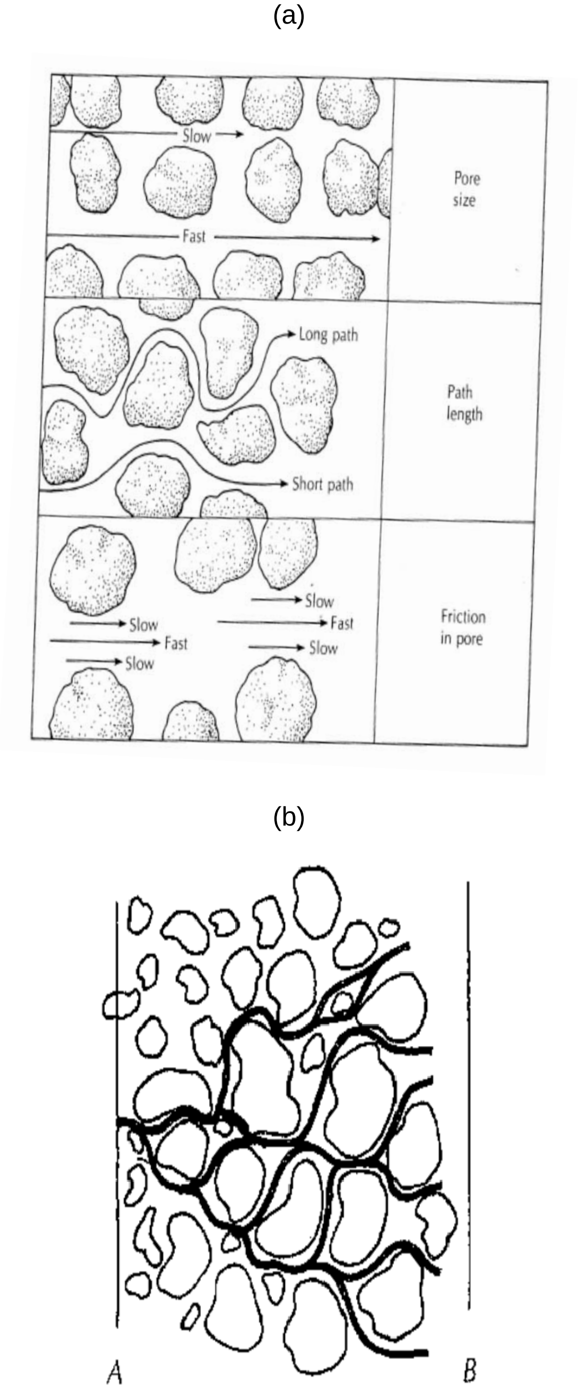


Figure 9-1: (a) Factors causing pore-scale longitudinal dispersion and (b) flow paths in a porous medium that cause lateral hydrodynamic dispersion (from Fetter, 2001).

9.3.2.2 Hydrodynamic Dispersion

Dispersion of the solutes dissolved in groundwater also occurs by diffusion, i.e. movement of solutes from a region of high concentration to a region of low concentration. The processes of molecular diffusion and mechanical dispersion cannot be separated in flowing groundwater. Instead, a factor termed the coefficient of hydrodynamic dispersion (D_L) is introduced. It takes into account both the mechanical mixing and diffusion (Fetter, 2001). For one-dimensional flow it is represented by the following equation:

$D_L = \alpha_L \times v + D^*$

Where:
D_L = longitudinal coefficient of hydrodynamic dispersion (in L^2/T)
α_L = longitudinal dispersivity (L)
D^* = the effective molecular diffusion coefficient (L^2/T)

At the field scale, hydrodynamic dispersion also occurs in the direction normal to flow which requires definition of the coefficient of hydrodynamic dispersion in the transverse and vertical direction.

In most groundwater flow systems, mechanical dispersion dominates dispersion and diffusion is insignificant. However, diffusion can be an important process in low permeability environments and/or in heterogeneous systems where diffusion facilitates exchange between active and stagnant flow zones (e.g. in dual porosity systems).

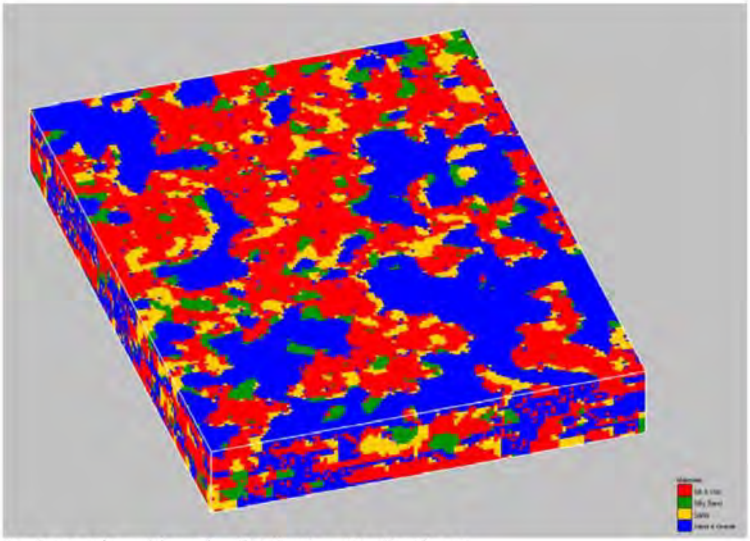
The relative contribution of diffusion and dispersion processes should be established as part of the conceptual model development.

9.3.2.3 Dispersion at the Field Scale (Macrodispersion)

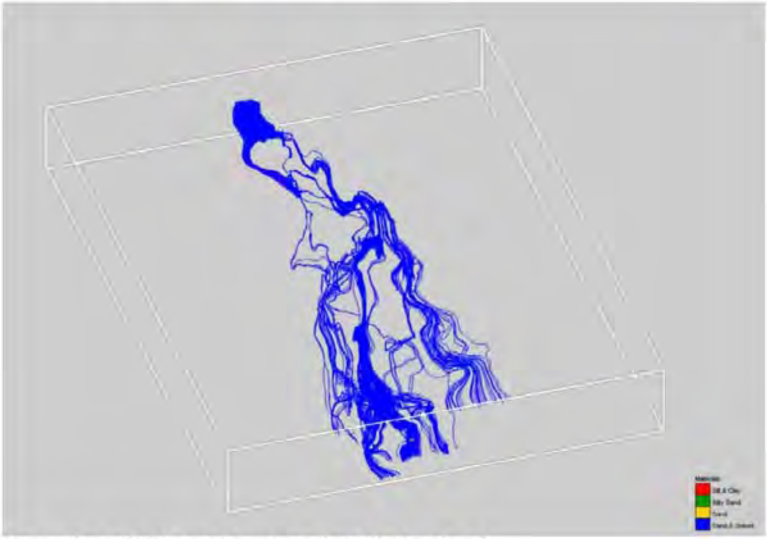
Mechanical dispersion is also caused by the heterogeneities in the aquifer. As groundwater flow proceeds in an aquifer, regions of greater than average hydraulic conductivity, and regions of lesser than average hydraulic conductivity are encountered. The resulting variation in linear groundwater velocity results in much greater hydrodynamic dispersion than that caused by the pore-scale effects (Fetter, 2001). This macro-scale dispersion effect is also known as “macro-dispersion”.

Macro-dispersion is influenced by the type and degree of heterogeneity and is difficult to quantify in a simple mathematical formulation commonly used in solute transport models (such as the dispersion equation shown above).

Figure 9-2 illustrates macro-dispersion in a heterogeneous porous medium. In this hypothetical (numerical) example, advective transport through a heterogeneous porous medium was simulated (using particle tracking). Pore-scale dispersion was ignored in this simulation. This example illustrates that the solute plume moves preferentially through high permeability zones resulting in significant localized channeling. Transport velocities and solute concentrations in those preferential flow channels can be significantly higher than would be predicted if a homogeneous aquifer and a standard dispersion model (with average properties) would be assumed for solute transport predictions.



Hydrostratigraphic units distribution. Realization 1



Streamlines (fluid particle trajectories). Realization 1

Figure 9-2: Macro-dispersion in a heterogeneous, porous medium. The upper panel shows the explicit representation of aquifer heterogeneity. The lower panel shows the resulting macro-dispersion simulated using particle tracking (dispersion at the pore-scale was not modeled).

Macrodispersion in fractured bedrock depends on the hydraulic properties of the fracture network (i.e. fracture density and connectivity, fracture aperture) and the matrix porosity (Beth et al., 2011). In densely fractured bedrock, solute transport occurs in a large number of fractures and transverse dispersion (i.e., plume spreading orthogonal to groundwater flow) is strong, similar to what is observed in a uniform porous medium (see Figure 9-3a). In sparsely fractured bedrock, the solute plume is channeled or funneled into narrow zones due to the dominance of flow in one or a few large, major fractures or fracture zones extending over long distances (Beth et al., 2001). In this case, the plumes would become long and narrow or 'snake-like' in shape rather than fan shaped (see Figure 9-3b). These plumes could extend for significant distances from the source locations with limited dispersion and hence dilution.

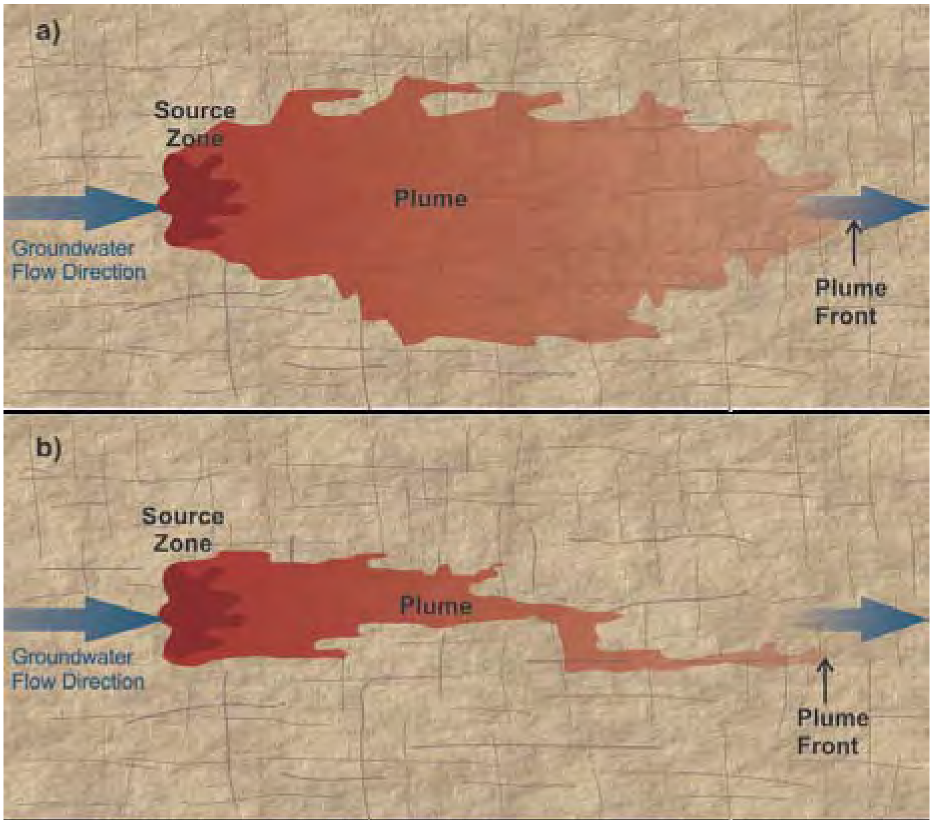


Figure 9-3: Macrodispersion in a heterogeneous porous medium (reproduced from Beth et al., 2011).

Figure 9-4 shows an example of macro-dispersion in fractured bedrock in which advective transport occurs in discrete fractures (e.g. bedding planes) but the rock porosity supports diffusion-driven solute mass transfer between the fractures (typical for sedimentary rocks). In this scenario, diffusion could significantly retard the advance of the solute plume (similar to a porous medium) but spreading of the solute plume would still not be random but instead follow the main orientation of the fracture network.

The influence of aquifer type (bedrock versus porous medium) and degree of heterogeneity (and/or degree of fracturing) on macro-dispersion should be considered when selecting the appropriate dispersion model and numerical values of dispersivity. For example, the presence of a few discrete fractures may require an explicit representation of these discrete features and advective transport only (no hydrodynamic dispersion). Alternatively, densely fractured bedrock may be adequately represented using the equivalent porous medium approach and using the hydrodynamic dispersion equation.

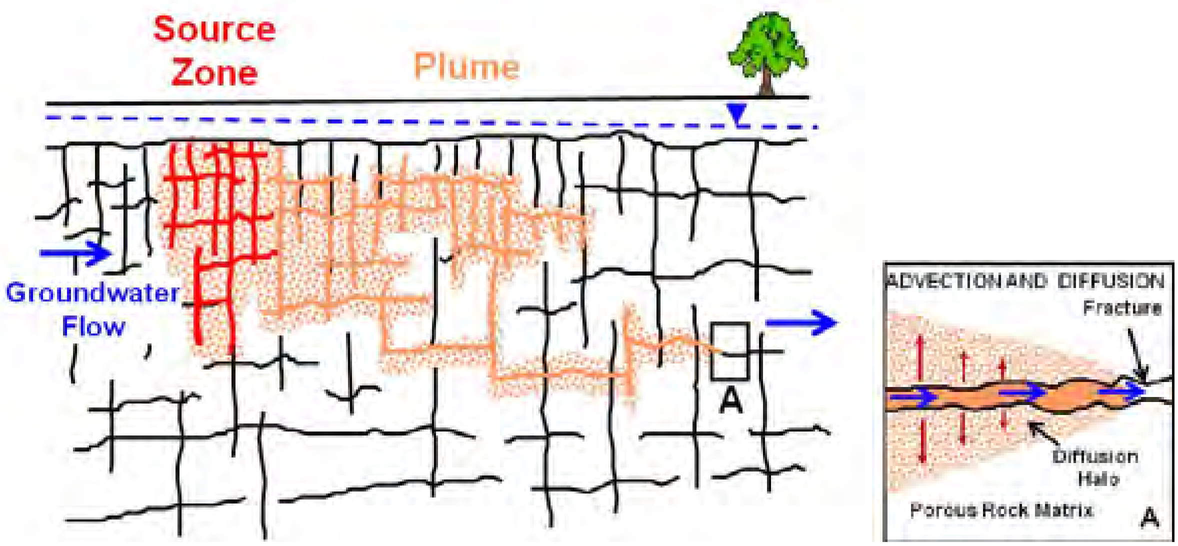


Figure 9-4: Macrodispersion in a fractured network (reproduced from Beth et al., 2011).

9.3.2.4 Scale Dependency of Dispersion

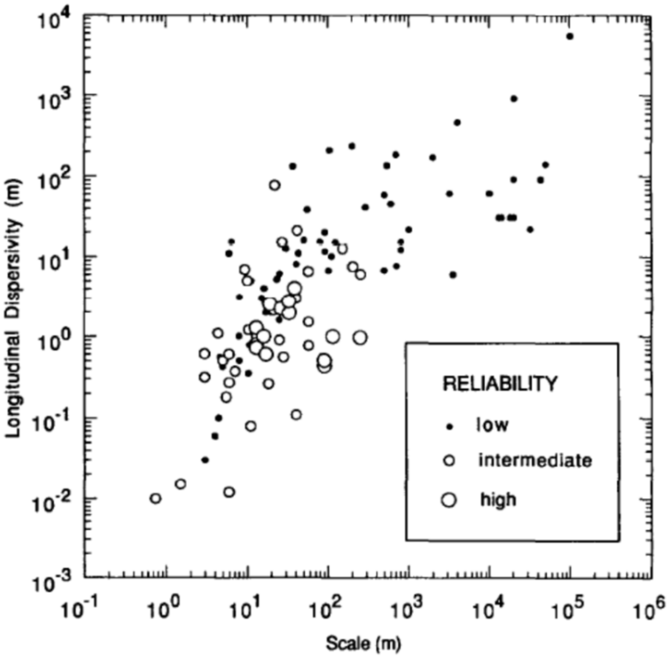
A review of a large number of transport studies indicated that dispersion is scale dependent, i.e. dispersivity increases with transport distance (see Figure 9-5a and 9-5b reproduced from Gelhar et al., 1992). Dispersivity values obtained from laboratory experiments (column tests) were typically one to two order of magnitudes lower than dispersivity values obtained from field tests (tracer tests, contaminated sites). However, a detailed assessment of the field studies indicated that the majority of the larger-scale field studies are unreliable.

The observed scale dependency of dispersivity values introduces uncertainty into solute transport predictions. For example, modelling of solute transport at the regional scale may justify the use of a larger dispersivity value. However, the use of a large-scale dispersivity value may overpredict the effects of dispersion at the local scale.

The measurement of dispersion is difficult and expensive in the field and consequently empirical expressions are almost always used. Gelhar et al. (1992) point out that the use of a large dispersivity value (in the upper end of a given scale) could result in the prediction of excessively large dilution which could result in non-conservative predictions of contaminant concentrations. They therefore recommend the use of dispersivity values from the lower third of a given scale shown in Figures 9-5a and 9-5b).

Note also that scale dependency of dispersion is strongly influenced by the influence of heterogeneity on dispersion (see above). It follows that the appropriate value of dispersivity for a numerical model will depend on the degree of heterogeneity explicitly included in the model. For example, if the local heterogeneity is well-represented in the numerical model (see Figure 9-2) then a smaller dispersivity value should be selected that matches the scale of the heterogeneity represented in the model.

(a)



(b)

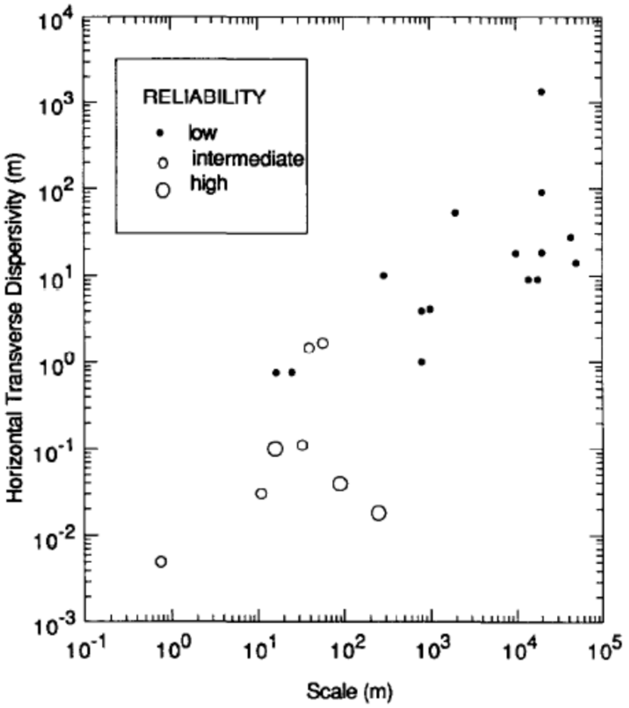


Figure 9-5: (a) Longitudinal dispersivity versus scale with data classified by reliability and (b) horizontal transverse dispersivity as a function of observation scale (from Gelhar et al., 1992).

These guidelines recommend the use of dispersivity values at the lower end of the reported range of values for a given scale (see Figures 9-5a/b). For typical basin-scale transport problems, longitudinal dispersivity values are usually in the range of 2 to 10 metres. Lateral transverse dispersivity values should be about one order of magnitude lower and vertical transverse dispersivity values should be about one to two order of magnitudes lower than longitudinal dispersivity.

The scale dependency of solute dispersion and the degree of heterogeneity represented in the numerical model is an important consideration in selecting an appropriate numerical value for dispersivity in the mathematical model and should be discussed in the conceptual model.

9.3.2.5 Influence of Dispersion on Solute Transport

Dispersion influences solute transport in three ways (see Figure 9-6):

- ➢ Longitudinal dispersion tends to spread out the breakthrough of a solute, resulting in earlier breakthrough of a solute (typically at low concentrations) than predicted based on the (average) advective velocity (Figure 9-6a)
- ➢ Transverse dispersion tends to spread out the lateral (and vertical) extent of the solute plume, resulting in greater spatial impacts than would be predicted using advection only (Figure 9-6b)
- ➢ Longitudinal and transverse dispersion tend to dilute the solute concentrations; this dilution effect is most pronounced in the case of a source term of short duration (e.g. a contaminant spill) (Figure 9-6c).

The consideration of dispersion tends to provide conservative water quality predictions with respect to first arrival times and maximum spatial extent of impact but tends to be non-conservative with respect to predicting actual contaminant concentrations at specific locations.

The effects of dispersion on solute transport require careful consideration by the modeller during model conceptualization and numerical modelling. To this end the following general guidelines should be followed:

- ➢ The nature and magnitude of solute dispersion and its potential effect on solute transport for the specific project should be discussed in the conceptual model
- ➢ The numerical value used for longitudinal and transverse dispersivity should be justified (default values by the model code are not acceptable without justification)
- ➢ If dispersivity values cannot be calibrated, a sensitivity analysis should be completed to determine the sensitivity of solute transport predictions to the uncertainty of this important transport parameter
- ➢ The influence of large-scale heterogeneity on dispersion and solute transport predictions should be discussed in the modelling report
- ➢ The limitations of the dispersion model used for simulating solute transport in the specific subsurface environment should be discussed in the modelling report.

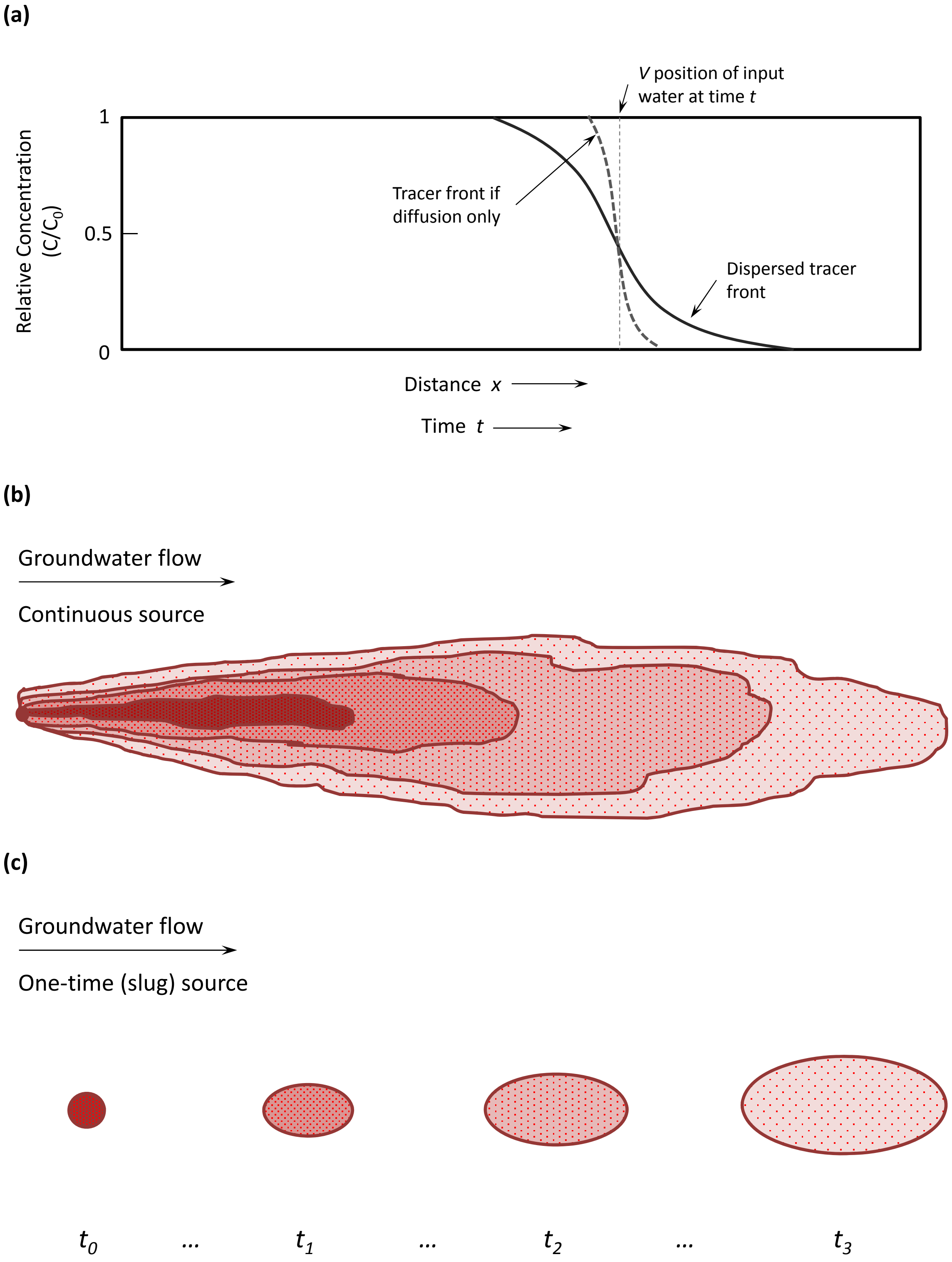


Figure 9-6: (a) Influence of dispersion and diffusion on "breakthrough" of a solute, (b) development of contaminant plume from a continuous point source, and (c) travel of a contaminant slug from a one-time point source. Density of dots indicates solute concentration (after Fetter, 2001).

9.4 GEOCHEMICAL TRANSPORT PROCESSES

The most common geochemical transport processes include:

- Sorption/desorption
- Precipitation/dissolution
- Degradation

Other chemical processes such as speciation, redox reactions, acid-base reactions, and volatilization may also influence solute concentrations but are not discussed further in these guidelines (see for example Appello and Postma, 2009 for more details on those processes).

The following sections provide a very brief overview of these three chemical transport processes. A more detailed discussion is provided in textbooks on aqueous geochemistry (e.g. Domenico and Schwartz, 1990; Appello and Postma, 2009).

9.4.1 Sorption/Desorption

Sorption processes include adsorption, absorption, chemisorption and cation exchange. These processes are complex and are dependent on the geochemical environment, the rate of groundwater flow, the surface area in contact with groundwater and the concentration of contaminants present in groundwater (NGCLC, 2001).

Different conceptual models have been developed to quantify sorption and desorption. Most sorption models are defined by a sorption isotherm, which describes the relationship of the solute concentration dissolved in groundwater and the solute concentration sorbed on the solid phase (i.e. soil particles or bedrock surface).

The following three sorption models are common (e.g. Appello and Postma, 2009):

- Linear isotherm
- Freundlich isotherm
- Langmuir isotherm.

The linear isotherm is the most common sorption model used in solute transport modelling. This model assumes that the quantity sorbed is directly proportional to the concentration in the groundwater and that sorption is instantaneous and reversible. Under those assumptions the travel velocity of a sorbing solute is reduced (relative to the average linear velocity of water) by a factor known as the retardation factor. The slope of the linear isotherm is known as the partition coefficient (k_D) and can be used to estimate the retardation factor (R_f).

This “retardation approach” does not apply to situations where the amount of sorption sites is limited (e.g. for major ions limited by the cation exchange capacity) and/or where sorption is not fully reversible (e.g. for sorption of some trace metals such as cobalt which exhibit “ageing”). In the first situation a non-linear isothern (e.g. Freundlich or Langmuir isotherm) can be used. The second situation may require the use of a kinetic sorption model (with different rates for sorption and desorption).

The selection of an appropriate sorption model will require an in-depth review of the site-specific geochemical conditions, including the CoC, ambient groundwater quality (e.g. pH, redox conditions) and the solid substrate. The use of sorption and selection of a particular sorption model for solute transport modelling should be justified based on site-specific monitoring and/or testing. Sorption parameters should be determined using field and/or laboratory testing which replicate in-situ geochemical conditions (i.e. local soils and in-situ pH and redox conditions).

9.4.2 Precipitation/Dissolution

Transport of selected solutes may also be influenced by precipitation/dissolution reactions. The solid phase of the aquifer (soil or bedrock) comprises minerals which in turn consist of an assemblage of major ions and trace metals. When the groundwater is in contact with these minerals, the mineral (e.g. calcite) will dissolve into its mineral components (in this example calcium and bicarbonate). The dissolution of natural minerals may also release trace metals. For example, elevated concentrations of trace metals are commonly found in mineralized areas where mining takes place.

Mineral precipitation is the reverse process of mineral dissolution. In mineral precipitation, the mineral constituents dissolved in groundwater bond together to form a mineral, i.e. they will precipitate out of solution. Precipitation and dissolution are controlled by the “solubility product” (or K_{sp}). A smaller solubility product indicates that the mineral is less soluble and that the concentrations of the mineral constituents dissolved in groundwater will be smaller.

The most common precipitation/dissolution reactions in groundwater in the context of natural resource projects include

- Precipitation/dissolution of common minerals such as calcite, dolomite and gypsum
- Precipitation/dissolution of iron-oxi-hydroxides and
- Co-precipitation of trace metals.

The precipitation of iron-oxi-hydroxides is of particular importance because they often result in co-precipitation of trace metals which can be of environmental significance. Precipitation of these oxi-hydroxides typically occur where reducing groundwater with elevated iron discharges and comes in contact with oxygen (e.g. in pumping wells, drains and/or at springs).

A significant body of research is available on the subject and the reader is referred to geochemical textbooks (e.g. Appello and Postma, 2009) and the scientific literature for more details.

Sophisticated multi-species solute transport models are available to simulate the influence of precipitation/dissolution reactions on solute transport (e.g., PHREEQC). However, such geochemical models are not routinely used for assessment of solute transport at the field scale.

The conceptual model of solute transport should discuss the potential influence of precipitation/dissolution reactions on solute transport. If justified, the potential influence of such geochemical controls on solute transport may be demonstrated using a simplified transport model (e.g. along a 1D flow path). However, the incorporation of precipitation/dissolution reactions into a basin-wide solute transport model is not recommended.

9.4.3 Degradation

Degradation can be a significant process in decreasing the contaminant mass of organic compounds in which case the process is called biodegradation. This process is complicated and the actual rate of biodegradation varies according to a range of factors including contaminant type, microbe type, redox, temperature and chemical composition of groundwater.

Radioactive materials will also experience degradation due to radioactive decay.

This process is usually represented mathematically either as a first order reaction (exponential decay), or by a rate limited reaction. Exponential degradation implies that the rate of decrease in concentration of the substance is proportional to the amount of substance and can be characterized by a half-life (i.e. it is assumed to be a first order reaction) (NGCLC, 2001). This behaviour is commonly observed in biodegradation (since the activity of a microbial population is proportional to the availability of its food), radioactive decay, and in other non-biological processes where the contaminant is present in trace amounts relative to other reactants.

The use of degradation in a solute transport model will require an in-depth review of the properties of the CoC and site-specific geochemical conditions potentially favoring degradation. The use of degradation and selection of a particular degradation model for solute transport modelling should be justified based on site-specific monitoring and/or testing.

9.4.4 Use of Geochemical Transport Processes for Natural Resource Projects

The use of geochemical transport processes for solute transport modelling tends be non-conservative, i.e. typically result in predictions of delayed and/or or reduced contaminant concentrations at potential receptors (e.g. stream or lakes).

For this reason, geochemical processes should only be included in the solute transport model if the presence of such processes can be demonstrated using site-specific observations and the geochemical model can be parameterized (e.g. using site-specific field data and/or lab testing).

If geochemical processes are included in solute transport modelling, a detailed sensitivity analysis should be included to demonstrate the influence of uncertainty in reactive transport parameters (e.g. k_D value) on the water quality predictions. This sensitivity analysis should always include a simulation of conservative solute transport (i.e. without geochemical controls) to allow an assessment of the influence of the assumed geochemical reactions on water quality predictions.

9.5 NUMERICAL METHODS OF SOLUTE TRANSPORT

9.5.1 Solution Methods

Several numerical methods are available to solve the advection-dispersion equation for solute transport (NGCLC, 2001):

- Eulerian method
- Lagrangian method
- Mixed Eulerian-Lagrangian method

9.5.1.1 Eulerian Methods

Eulerian methods involve approximate solutions to the equations governing contaminant transport by advection and dispersion. These methods can be subject to numerical instability, artificial oscillations and numerical dispersion when compared to exact analytical solutions (see Section 9.5.2 for more details).

The numerical problems associated with the Eulerian method makes this method less attractive for solute transport problems (see Section 9.5.2).

9.5.1.2 Lagrangian Method

The Lagrangian methods represent solute transport by a large number of moving particles to avoid solving the advection transport equation. The method is free of numerical dispersion, although numerical problems may be associated with irregular grids or contaminant sources or sinks. The method is most suited to problems where advection dominates contaminant transport.

9.5.1.3 Mixed Eulerian - Lagrangian Approach

The Mixed Eulerian - Lagrangian approach combines the advantages of these two techniques and uses the Lagrangian approach to solve the advection term and the Eulerian approach to solve the dispersion term. The Method of Characteristics (“MOC”), the Modified Method of Characteristics (“MMOC”), and the Hybrid Method of Characteristics (“HMOC”) are examples of this approach.

The mixed Eulerian-Lagrangian approach is often the preferred solution method for solute transport problems, in particular when both advection and dispersion are important transport processes.

9.5.2 Numerical Problems with Solute Transport Models

The two most common numerical problems with solute transport models are:

- Numerical dispersion
- Numerical instability

The following sections describe these numerical issues and provide guidance on how to avoid them.

9.5.2.1 Numerical Dispersion

A common problem in running numerical models of solute transport is numerical dispersion. Numerical dispersion results in artificial spreading of the solute plume due to inaccuracies in the numerical solution. Figure 9-7a illustrates the effect of numerical dispersion. Numerical dispersion is usually caused by insufficient discretization in space and/or time.

Numerical dispersion occurs in all three principal directions but is often most pronounced in the vertical direction because the vertical discretization in 3D models tends to be less than in the x-y plane.

Numerical dispersion can be minimized by a number of methods:

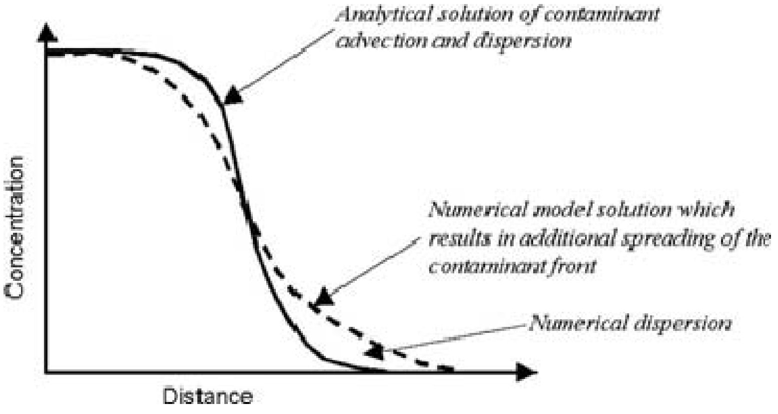
- Decreasing the model grid spacing and time step to minimize dispersion particularly for models that are solved by Eulerian methods (Appendix E); however, this will increase model run times;
- Choice of the solution method; for example, Lagrangian methods are less susceptible to numerical dispersion;
- Choice of initial or starting conditions;
- Choice of convergence criteria for the model.

The degree of numerical dispersion should always be checked by gradually reducing the dispersivity until the numerical solution does not change any longer. The remaining dispersion (deviation from advective transport) is due to numerical dispersion. Numerical dispersion is acceptable if it is much smaller than the dispersion due to the dispersivity of the natural aquifer system.

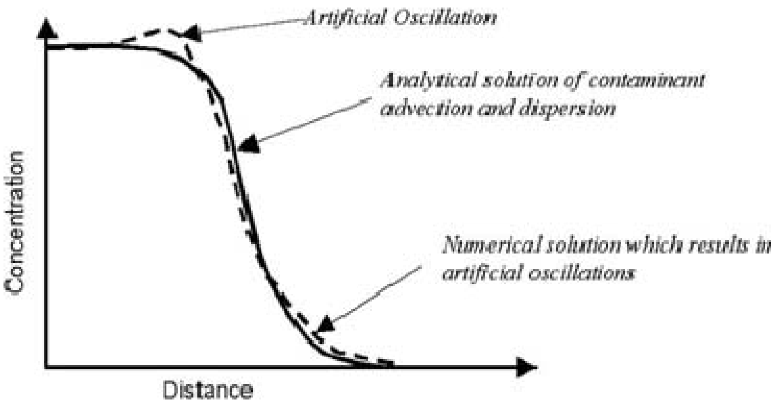
9.5.2.2 Numerical Instability

The advection-dispersion equation is difficult to solve by numerical methods and may result in model instability, in particular if standard finite-element or finite difference schemes are used.

a) Numerical Dispersion



b) Numerical (or Artificial) Oscillation



c) Numerical Instability

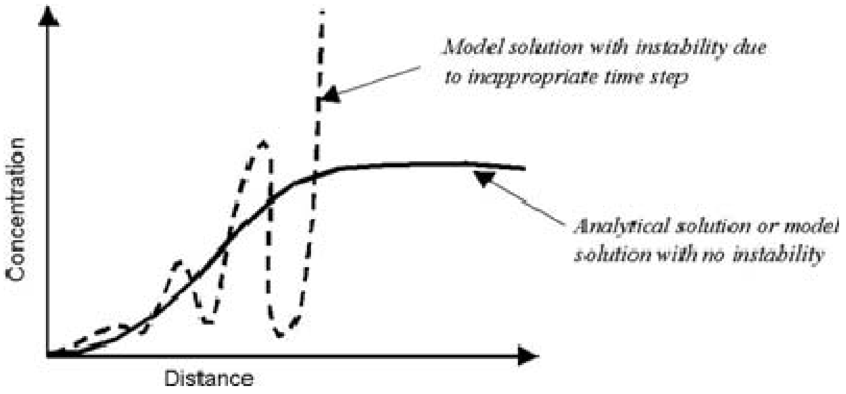


Figure 9-7: Illustrative examples of numerical problems in solute transport modelling (Reproduced from NGCLC, 2001)

Numerical instability in the transport model can lead to numerical oscillations in space and/or time (see Figure 9-7b/c).The modeller (or reviewer) should always check the transport solutions for such oscillations which indicate the presence of numerical instability.

In general, the likelihood of model instability increases with a coarser discretization in space and time. These guidelines recommend that the maximum grid size and time step for solute transport be estimated using common criteria known as the grid Peclet number and Courant number (see Appendix E). In addition, the effect of grid spacing and time stepping on the solute transport solution should be evaluated using sensitivity analyses.

9.5.2.3 Review of Numerical Problems

The following checks should be performed by the modeller (or reviewer) to determine whether there are problems with the numerical solution of the solute transport problem (NGCLC, 2001):

- Mass Balance: Errors in the mass balance provide evidence of numerical instability
- Time Series: Oscillations in predicted contaminant concentrations with time may indicate instability
- Contaminant Distribution: Anomalies in contaminant distributions may also indicate instability.

9.6 COMMON TRANSPORT PROBLEMS IN NATURAL RESOURCE PROJECTS

Solute transport modelling is usually required to assess potential water quality impacts by a proposed natural resource project, typically to nearby valued ecosystem components (VECs) such as a drinking water well, fish-bearing creeks or lakes. Solute transport modelling is more commonly required for mining projects which can produce seepage from mine waste units (TSFs, WRDs) with poor water quality (elevated TDS and/or metals). Most aggregate mining and groundwater extraction projects do not impact water quality and therefore do not require solute transport modelling.

Typical modelling objectives requiring solute transport include:

- Predict pathway and travel time of a solute in a steady-state (or transient) groundwater flow field
- Predict spatial and temporal evolution of a solute plume in the aquifer (from source to receptor)
- Predict “breakthrough” of a solute (i.e. concentration versus time) at a receptor (e.g. private well, reach of lake or stream)
- Predict solute loading to surface water (lake /stream)
- Design of mitigation measures such as
  - Natural attenuation
  - Seepage interception system (SIS)
  - Pump & treat
  - Reactive barriers
- Predict recovery of solute load in seepage interception system.

Particle tracking is usually adequate to determine pathways and average travel times. Figure 9-8a/b shows an example of the use of particle tracking to determine the efficacy of a deep drain to intercept seepage from a tailings dam. In this example, the depth of the drain was varied until all particles are captured in the drain, demonstrating that full hydraulic capture is achieved. For this design, the water quality (contaminant concentrations) in the intercepted seepage was not important (all intercepted water is recycled to the tailings impoundment). Hence, a solute transport model was not required.

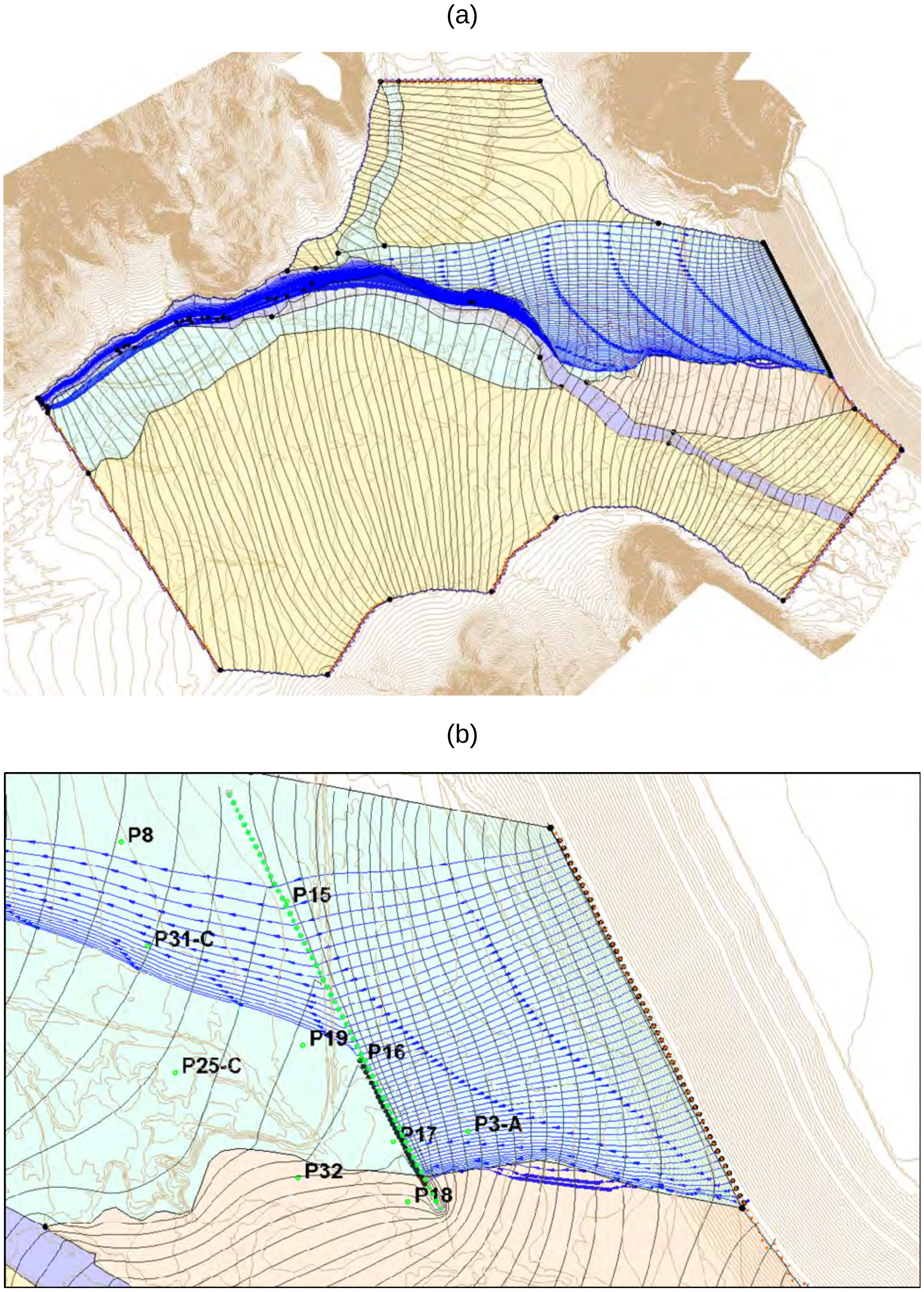


Figure 9-8: Example of particle tracking for design of seepage interception system, The upper panel shows the pathlines of seepage (advective transport) prior to seepage interception. The lower panel shows the pathlines of seepage after installation of a partially penetrating drain (arrow = 100 days). In this example, the design depth of the drain was not sufficient allowing underflow beneath the drain in the northern portion.

In some cases, particle tracking may even be sufficient to estimate solute loads to a VEC. Figure 9-9 illustrates an example where the average solute load from a waste rock dump to a nearby creek had to be estimated. Particle tracking was completed to estimate the reach of the creek impacted by seepage from the waste rock pile. The average travel time from the waste rock dump to the creek was estimated to be only a few years. Since the waste rock dump had been placed several decades ago it could be assumed that that the seepage plume had reached a pseudo steady-state. Therefore, the solute load reaching this particular reach of the creek could be (conservatively) assumed to be equal to the net infiltration into the waste rock dump times the average solute concentration (known from piezometers installed in the waste rock dump).

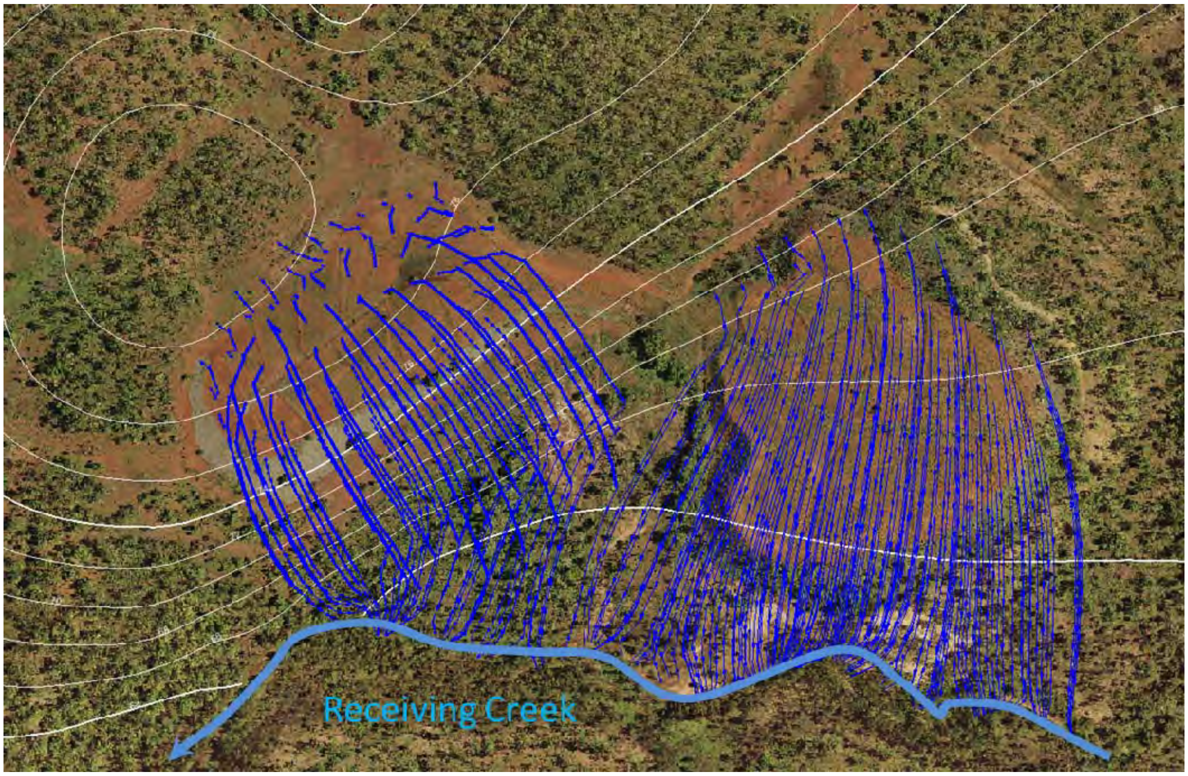


Figure 9-9: Example of particle tracking used to estimate contaminant load from a waste rock dump (right) and backfilled open pit (left) to a near-by creek. The blue lines illustrate the pathlines of seepage from the two mine waste units and the reach of the creek

Note that particle tracking does not provide any insight into the degree of dispersion (in the aquifer) and dilution (by local recharge) along the flow path and hence the solute concentration in groundwater emerging into the creek. However, these processes did not need to be simulated in this example because solute loads (not actual solute concentrations) were required for this impact assessment.

In general, solute transport models are used when a prediction of solute concentrations (in space and/or time) is required. In the context of an EA, solute transport models are often used to predict solute concentrations in groundwater or surface water which are then compared to numerical water quality standards (e.g. BC Water Quality Guidelines or site-specific water quality objectives). Figure 9-10 shows the predicted evolution of a sulphate plume due to seepage from a tailings dam. This model was first calibrated using observed sulphate concentrations in a series of monitoring wells. Once calibrated, the solute transport model was then used to design seepage mitigation measures required to meet applicable water quality guidelines at the downgradient boundary.

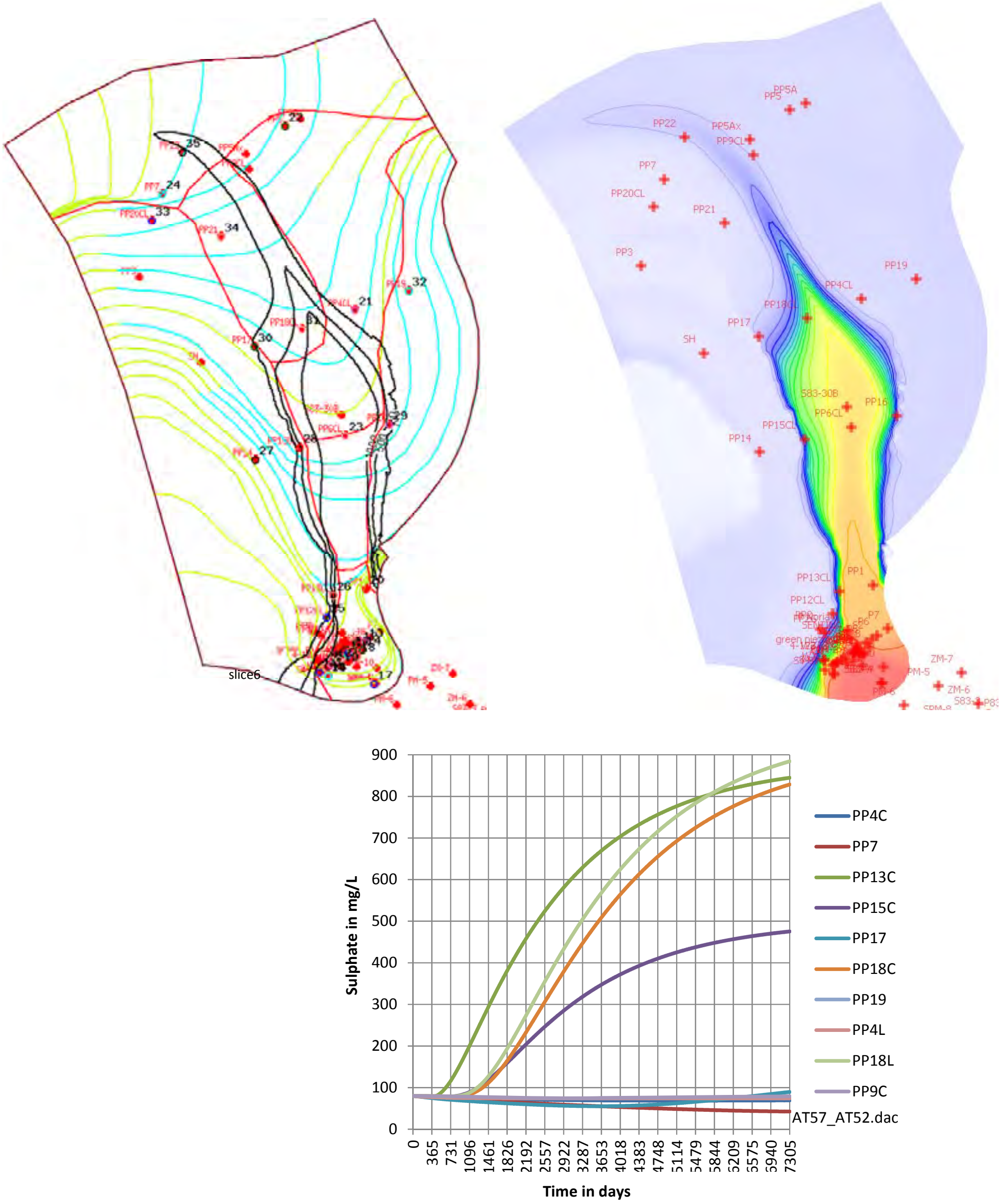


Figure 9-10: Example of solute transport modelling used to predict movement of a sulphate plume. The upper panels show the simulated spatial extent of the sulphate plume after 30 years. The lower inset plot shows the simulated breakthrough of sulphate at different monitoring locations.

It should be recognized that predictions of solute concentrations for specific locations (e.g. a compliance point) carry significantly greater uncertainty than predictions of solute loads to a general area (e.g. to a stream reach). This applies in particular for heterogeneous porous media and fractured media, where preferential flow paths exist but are usually not well understood.

For this reason, the modeller should always discuss the limitations in predicting solute concentrations at specific locations (or receptors) and should provide recommendations as to the appropriate use of such solute transport predictions in the regulatory context.

9.7 CALIBRATION OF SOLUTE TRANSPORT MODELS

Solute transport modelling requires knowledge about the groundwater flow field. In most cases a groundwater flow model is first calibrated (using observed groundwater levels (or hydraulic heads) and/or observed flows (see Section 7). In a subsequent step, the solute transport model is then calibrated using observed solute concentrations (e.g. spatial distribution and/or time trends). It is emphasized that the use of a calibrated groundwater flow model is a requirement for solute transport modelling. However, the use of a calibrated flow model does not imply that the solute transport model is calibrated. The transport parameters (such as effective porosity, dispersivity and reactive transport parameters) can only be calibrated by matching simulated and observed spatial and/or temporal distributions of a solute.

A common problem in applying solute transport models to natural resource projects is the lack of suitable monitoring data available for model calibration. Significant changes to the groundwater quality (such as seepage from a mine waste unit resulting in a solute plume) usually do not occur until after start of the project. For example, seepage from a proposed tailings impoundment clearly does not occur until after the project is permitted and operation has started. In fact, it may take many years to decades before a solute plume has migrated into the aquifer and can be used for model calibration.

It follows that most solute transport models used for EA submissions or permitting are not calibrated. Instead, transport parameters such as effective porosity and dispersivity have to be selected based on analogue sites and/or experience by the modeller. This lack of model calibration introduces uncertainty in solute transport predictions. The modeller should clearly state in the model documentation whether the solute transport model is calibrated. If the model is not calibrated, the model documentation should justify the selection of the solute transport parameters.

If the solute transport model is not calibrated, a detailed sensitivity analysis should be completed to evaluate the influence of uncertainty in solute transport parameters on transport predictions.

Calibration of a solute transport model may be possible at later stages of the project life, in particular at closure or post-closure, when a solute plume might have developed. During model conceptualization, the modeller should review current and historic groundwater quality data to determine whether suitable groundwater quality data are available to calibrate the solute transport model (see Section 4).

Calibration of a solute transport model provides significant insight not only into solute transport but also into groundwater flow. For example, the spatial distribution of a solute may indicate the presence of a high-permeability channel(s) (or a barrier to flow) that was not included in the groundwater flow model. In many cases, calibration of the solute transport model requires recalibration of the flow model and sometimes even a change in the conceptual model.

The combined calibration of a flow model (against heads and flow) and solute transport model (against concentrations and loads) significantly increases the confidence in model predictions of both flow and transport.

9.8 UNCERTAINTY IN SOLUTE TRANSPORT MODELLING

In general, predictions of solute transport carry significantly more uncertainty than prediction of groundwater flow for the following reasons:

- Solute transport parameters (effective porosity, dispersivity and reactive transport parameters) cannot be measured directly at the field scale; yet, measurements of these transport parameters at the laboratory scale (e.g. using column experiments) may not be directly applicable to the field scale due to scale effects (effective porosity, dispersivity) and/or different geochemical conditions (reactive transport parameters)
- The only reliable method to determine transport parameters is through calibration of a solute transport model; however, model calibration is often not possible because of a lack of calibration data, in particular during early stages of EA and project permitting
- Solute transport is strongly influenced by heterogeneity (macro-dispersion), in particular in fractured bedrock environments; even with implementation of a comprehensive drilling and hydraulic testing program, uncertainty about preferential flow paths will always remain (in particular in fractured bedrock)
- Most solutes are influenced by geochemical reactions which can be complex and difficult to represent by a simple mathematical model to be included in the solute transport model
- The transport of a solute is strongly influenced by the “source term”, i.e. the strength and timing of contaminant release from a contaminant source; however, the source term is often controlled by geochemical processes (such as sulphide oxidation and precipitation/dissolution reactions in sulphidic mine waste) which need to be estimated using geochemical models and carry their own uncertainty
- Solute transport is a slow process, with predictions for mining projects often covering decades to centuries; this large time frame adds additional uncertainty with respect to future conditions (e.g. future groundwater use, climate change).

The above uncertainties in solute transport modelling should be evaluated in a detailed uncertainty analysis (see also Section 8). Such an uncertainty analysis should include a qualitative discussion of all uncertainties in solute transport predictions and a quantitative assessment of key uncertainties, including the sensitivity of water quality predictions to uncertainty in macro-dispersion and uncertainty in geochemical controls.

Considering the uncertainty in solute transport modelling, conservative assumptions should be used as much as possible, in particular during the early stages of project life (EA application and/or permitting). Non-conservative assumptions (such as high dispersivity, sorption) should only be used if there is evidence from the project site (or a suitable analogue site) to support these non-conservative assumptions.

9.9 CASE STUDY EXAMPLE

9.9.1 Case Study 2: Underground Mine

Case Study 2 illustrates the application of a solute transport model to a mining project. In this project, total organic carbon (TOC) had been identified as a potential CoC and the transport of this CoC to nearby receptors (lakes and streams) was simulated (see Appendix C2).

Initially, particle tracking was used to estimate the advective path and travel times of seepage from the new adit, the underground stopes, and beneath the load-out facility post-flooding. Particle tracking confirmed that mine-related CoCs may reach groundwater discharge points several decades after closure (see Figure 9-11). The particle tracking exercise helped to identify potential receptors, but was not able to provide estimates of CoC concentration (see Section 5.6.2.2).

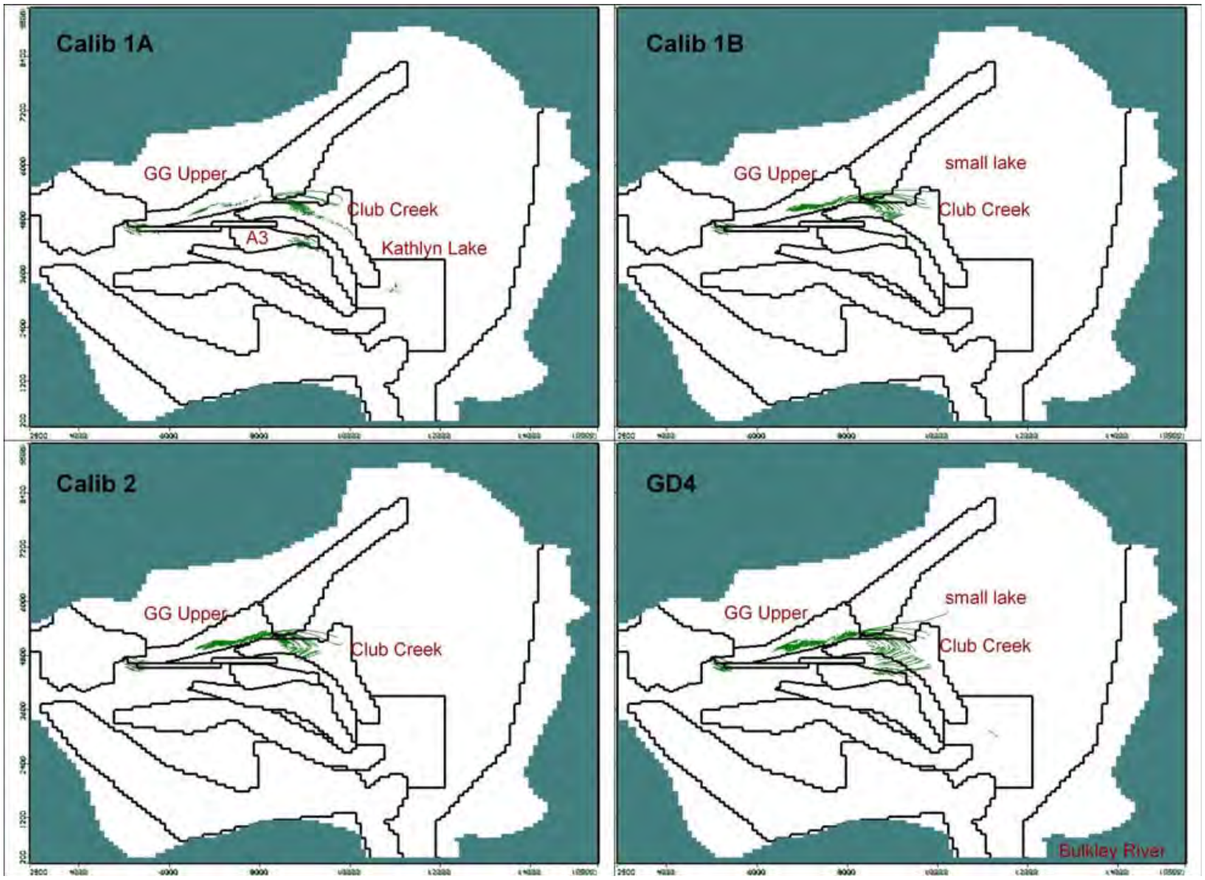


Figure 9-11: Pathline Endpoints from Particle Tracking Simulations, Calibration Runs and Worst-Case Hydraulic Parameters (GD4).

Subsequently, conservative and reactive solute transport modelling was undertaken to simulate the transport of total organic carbon (TOC) to the receiving environment. A single value representing the initial TOC concentration was assumed based on a consultant's report. The transport simulation was conducted as two separate scenarios: (i) where TOC does not react or degrade with time; and (ii) where TOC is reactive and decays with time.

Three observation wells were created in the model domain to track the break-through of TOC over time (Figure 9-12). These wells were located upstream of the sensitive receiving environments and distributed spatially (across the domain as well as with depth). The predicted break-through curves for TOC in these monitoring wells are shown in Figure 9-13.

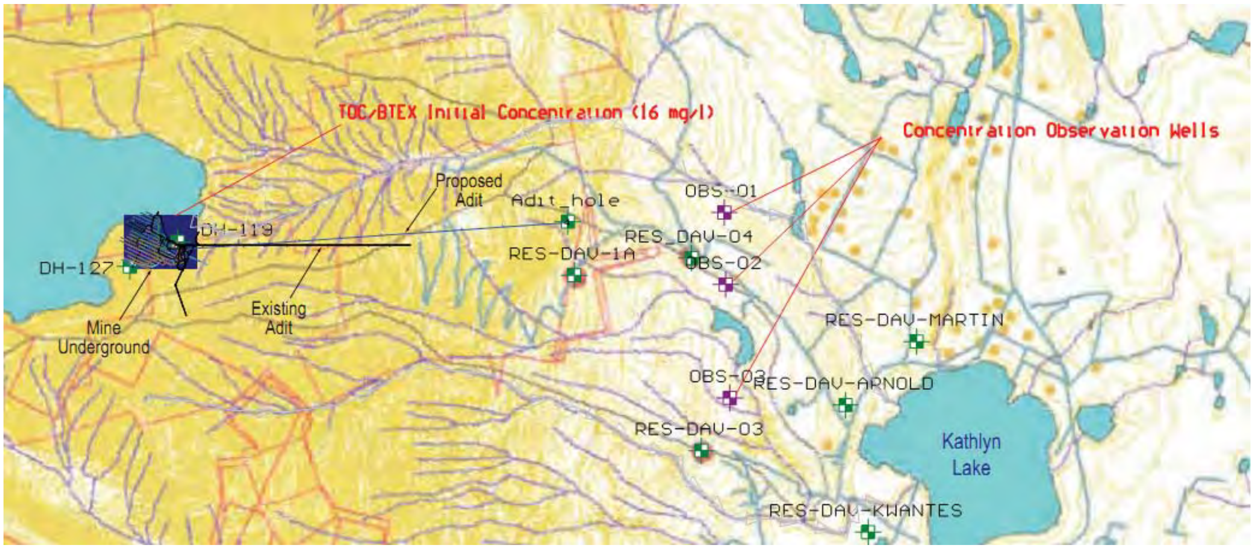


Figure 9-12: Location of simulated observation wells (purple) along with existing residential and monitoring wells (green)

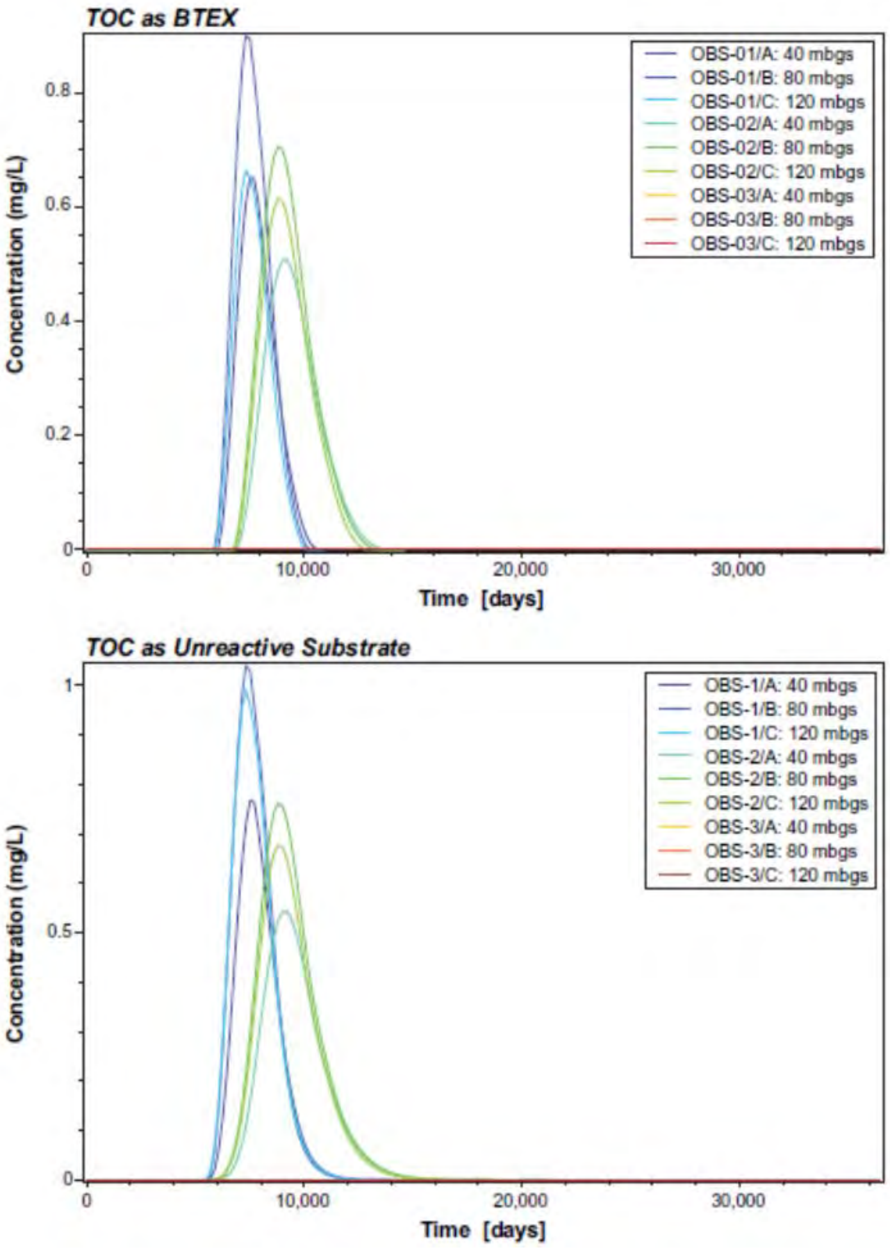


Figure 9-13: Predicted break-through curves for TOC assuming (a) biodegradation and (b) no biodegradation.

The transport model predicted a breakthrough of the TOC at two of the three observation points, with average arrival times ranging from about 20 to 30 years. The model predictions further indicated that the use of a first-order reaction rate (to simulate biodegradation) did not significantly influence the timing and peak concentrations of TOC (considering all other uncertainties).

At this point, an additional sensitivity analysis was performed to assess the effect of the shallow till hydraulic conductivity. The effect was to deflect particles towards different areas of the receiving environment (e.g. away from a lake and towards a river) which could have significant implications regarding receptor sensitivity and dilution capacity.

The transport module MT3D was used to simulate non-reactive transport of a non-specific mine-related CoC from the mine workings (representing 100% concentration). The default values for dispersivity were adopted (α_L=10m, α_{TH}=1m and α_{TV}=0.1m). Simulations of post-closure transport indicate that supply wells and surface water will not receive a significant percentage of the solute in the 100 year timeframe simulated (see Figures 9-14 and 9-15).

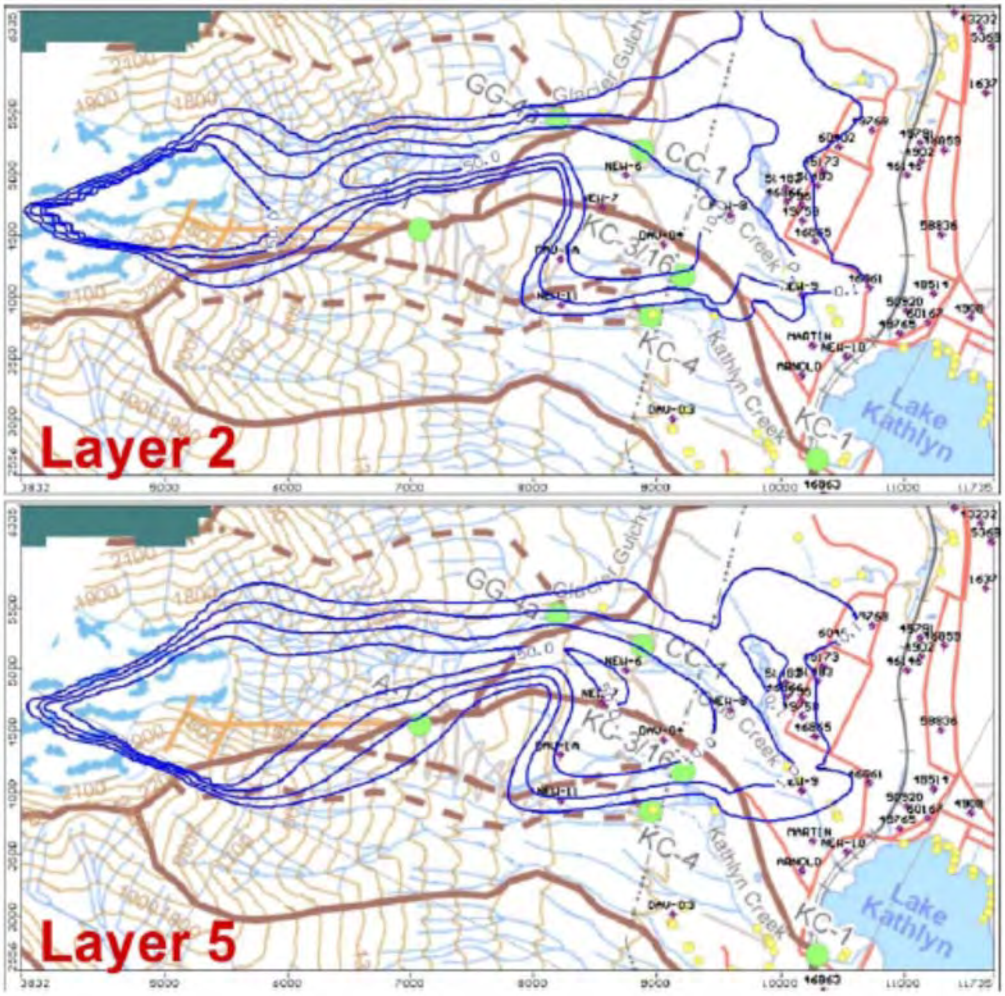


Figure 9-14: Predicted concentration contours (blue) at 100 years after mine closure for depths represented by Layers 2 and 5 of the model. Contours at 50, 10, 1, and 0.1% of mine concentration.

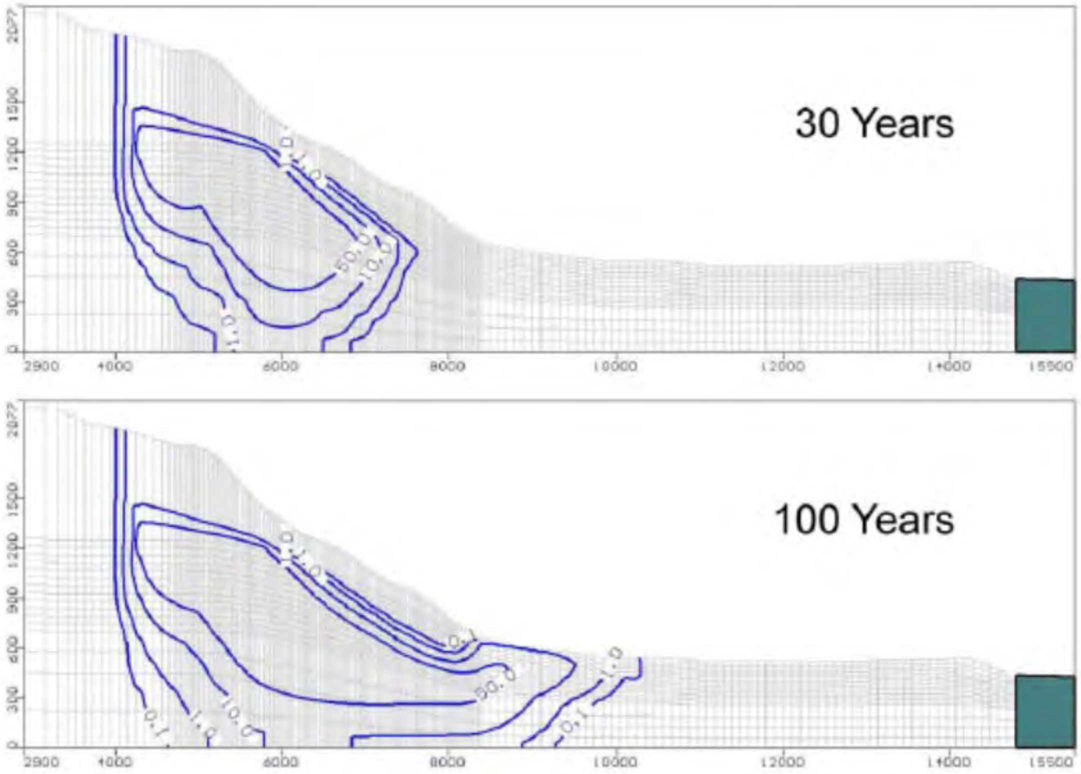


Figure 9-15: Vertical distribution of mine solute at 30 and 100 years after mine closure. Contours at 50, 10, 1, and 0.1% of mine concentration.

Additional analyses were performed with a subsequent model to show that the downstream supply wells would receive only 1% more groundwater from the mine area compared to pre-mining conditions. On the basis of transport simulations and the predicted path of the mine-affected plume, additional groundwater monitoring well locations were recommended by the modeller

This case study is typical for solute transport modelling completed for EA submissions in that (i) site-specific information on solute transport parameters was not available and (ii) the solute transport model was not calibrated. It follows that the uncertainty in these solute predictions is very high. The model study addressed the uncertainty in the groundwater flow predictions by simulating different conceptual flow models and performing additional sensitivity analyses (see Section 8). However, the study did not address all uncertainties in the solute transport predictions. For example, the uncertainty in macro-dispersion in this bedrock aquifer was not discussed nor quantified. The potential for numerical dispersion (in combination with use of the default dispersivity value) was also not evaluated.

Considering the remaining uncertainties, the solute transport predictions presented in this case study should be viewed as illustrative, describing the general pathway and general trends in solute plume behavior. However, the predictions of specific breakthrough curves at specific locations (such as wells) carry significant uncertainty. These model limitations should be considered when interpreting the solute transport predictions.

SUMMARY POINTS FOR TRANSPORT MODELLING

1. All solutes are influenced by the same physical transport processes, namely advection and dispersion. In contrast, geochemical transport processes (sorption, precipitation/dissolution, degradation) depend on the solute of interest as well as geochemical conditions in the aquifer.
2. Advective transport can be simulated very efficiently using particle tracking codes. Particle tracking should always be carried out prior to considering other transport processes using a full solute transport model.
3. The process of spreading and hence dilution of a solute along the flow path is known as dispersion. Dispersion occurs at the pore-scale and at the macroscopic (field) scale. The influence of aquifer type and degree of heterogeneity on macro-dispersion should be considered when selecting the appropriate dispersion model and numerical values of dispersivity.
4. The applicability of a sorption model should be justified based on site-specific monitoring and/or testing. Sorption parameters should be determined using field and/or laboratory testing which replicate in-situ geochemical conditions.
5. The conceptual model of solute transport should discuss the potential influence of precipitation/dissolution reactions on solute transport. If justified, the potential influence of such geochemical controls on solute transport may be demonstrated using a simplified transport model. However, the incorporation of precipitation/dissolution reactions into a basin-wide solute transport model is not recommended.
6. The use of degradation in a solute transport model will require an in-depth review of the properties of the CoC and site-specific geochemical conditions potentially favoring degradation. The applicability of a degradation model should be justified based on site-specific monitoring and/or testing.
7. If geochemical processes are included in solute transport modelling, a detailed sensitivity analysis should be included to demonstrate the influence of uncertainty in reactive transport parameters on the water quality predictions. This sensitivity analysis should always include a simulation of conservative solute transport (i.e. without geochemical controls) to allow an assessment of the influence of the assumed geochemical reactions on water quality predictions.
8. The use of a calibrated flow model does not imply that the solute transport model is calibrated. If the solute transport model is not calibrated, a detailed sensitivity analysis should be completed to evaluate the influence of uncertainty in solute transport parameters on transport predictions.
9. The modeller should always discuss the limitations in predicting solute concentrations at specific locations (or receptors) and should provide recommendations as to the appropriate use of such solute transport predictions in the regulatory context.
10. Considering the uncertainty in solute transport modelling, conservative assumptions should be used as much as possible, in particular during the early stages of project life (EA application and/or permitting). Non-conservative assumptions (such as high dispersivity, sorption) should only be used if there is evidence from the project site (or a suitable analogue site) to support these non-conservative assumptions.

10 MODEL DOCUMENTATION

10.1 GENERAL

This section describes documentation of groundwater models as submitted to the regulator for review and potential approval. Specifically, this section describes paper and electronic documentation provided to the regulator and hence the pubic as part of an EA or other permitting process. This section does not address model documentation by the proponent and their consultants. It is recognized that documentation procedures are company specific and that storage of paper and electronic files varies considerable from company to company.

10.2 OVERVIEW

There are two types of model documentation:

- Modelling Report – reports that describing the basis for the model, key assumptions, modelling approach, and the study findings, conclusions, and recommendations.
- Modelling Archives – a combination of modelling journals, documents on pre- and post-processing data analysis, and modelling data and software program files, such that the model could be re-generated for review and/or further refinement.

10.3 MINIMUM REQUIREMENTS OF SUBMITTED DOCUMENTATION

The primary requirements for documentation provided by a proponent to the regulator are clarity, transparency, and comprehensiveness.

The documentation provided by the proponent to the regulators should include sufficient detail to enable an independent party to replicate the modelling.

Documents provided by a proponent to the regulator are publically available. It is recognized that varying levels of public interest may be elicited by such documents. Accordingly, these guidelines recommend that reports be structured to provide for increasing levels of detail. For example, the following sequence of increasing documentation detail and specificity may be used:

- Executive Summary – generally no more than one to four pages.
- Technical Report – preferably no more than about twenty to thirty pages.
- Drawings, figures, and exhibits – large maps, computer output plots, or exhibits that provide specificity of site conditions, model layouts, and resultant model simulations.
- Technical Appendices – each should be topic specific and as long as is necessary to document the topic.
- Calculation Packages – each should be topic specific and of sufficient length and detail for the reviewer to independently check equations, calculations, and outcomes.
- Data Files – computer data files that may be used by an independent reviewer or investigator to rerun codes.

10.4 MODELLING REPORT

10.4.1 Interim Reports

Interim reports during the modelling process provide an opportunity to both communicate study status, issues and preliminary results, and to elicit feedback from regulators. The use of interim reports provides an opportunity to obtain agreement within both the proponent and regulator teams on such items as assumptions, data requirements, and analytical methods.

The requirements and schedule of interim reports should be established as part of the model study schedule.

If delivered to the regulator, such interim reports may become part of the official project record and hence publically available. Accordingly, interim reports should be clearly labeled as draft. Interim report should be made final and/or incorporated into the final report.

Topics of interim reports may include:

- Definition of model objectives
- Conceptual model development
- Completion of predictive models and uncertainty analysis.

10.4.2 Final Reports for Conceptual Models

Table 10-1 (modified from MDBC, 2001) summarizes recommended components and content for a final modelling report. These guidelines recognize that project specifics may dictate alternative report formats and contents. The proponent is urged to arrange the report as deemed necessary and appropriate to communicate work done, conclusions, and recommendations.

Table 10-1: Suggested Model Report Structure and Content (modified from MDBC, 2001)

Item	**Title**	**Detail** (as relevant for the objectives and complexity)
1	Study title	Select the title carefully to communicate the project goals, outcomes and/or the modelling objectives to the intended audience. Avoid simply using the site name.
2	Executive Summary	Summarize model development, management scenarios assessed, and the findings of the study. Briefly explain how the model was developed and refined. Summarize uncertainties, inadequacies, and possible methods of resolving these (e.g. by fieldwork and/or further model development).
3	Introduction	State the project objectives, model purpose, and complexity in specific and measurable terms. Introduce the study area and previous work. Describe the resource management issues.

Item	**Title**	**Detail** (as relevant for the objectives and complexity)
4	Data Review and Hydrogeological Setting	Describe the catchment geology, hydrology, and hydrogeology. Describe the data available. Collate the hydrogeological framework, parameters, stresses, and monitoring, and published information (e.g. literature review of papers, reports, etc.). Provide a brief overview of the natural resource development modeled (e.g. mine plan, pumping etc.)
5	Conceptual Model	Describe the current conceptual understanding of the aquifer system. Outline uncertainties and limitations. Describe the following aspects of the conceptual flow model (using tabular and graphical formats): a) aquifer types, geometry, and measured properties b) groundwater flow regime (direction, gradients) c) the spatial and temporal variation in natural recharge and discharge d) surface water-groundwater interactions (lakes, streams) e) groundwater abstractions (various uses) f) general influence of resource development g) water balance estimates Describe the following aspects of the conceptual contaminant transport model (if applicable): h) contaminants of concern (CoC) i) sources & sinks of CoC j) applicable transport processes
6	Numerical Model	Describe the conversion of the conceptual model into a numerical model. Describe the numerical methods (using tabular and graphical formats): a) code selection (including rationale) b) model domain & boundary conditions c) model layers & discretization of model grid d) recharge & evapotranspiration e) internal sinks & sources f) model parameterization g) simulation period, initial conditions & time stepping h) model convergence parameters i) methods of model calibration j) methods of sensitivity & uncertainty analysis Describe the numerical methods of transport model If applicable: k) selection of transport code & solution scheme (incl. rationale) l) boundary conditions for transport m) simulation period, initial conditions & time stepping n) methods of sensitivity & uncertainty analysis

Item	**Title**	**Detail** (as relevant for the objectives and complexity)
7	Model Calibration	Describe and discuss the qualitative and quantitative measures of calibration performance and sensitivity analysis for the model, including: a) water balances, including time series of components of the water budget and annual water balances b) iteration residual error c) lumped residuals and statistics, scattergram plots, etc. d) comprehensive comparisons between measured and modelled: • groundwater heads (maps, cross-sections, hydrographs, horizontal and vertical head gradients) • groundwater-surface water interaction (spring and river flow hydrographs, plots showing gaining and losing reaches of streams, etc.) e) the sensitivity/uncertainty analysis approach and outcomes. Describe and discuss the qualitative and quantitative measures of calibration performance and sensitivity analysis for **transport model** (if applicable), including: f) mass balances, including time series of components of the mass budget and annual mass balances g) comprehensive comparisons between measured and modelled: • CoC concentrations in groundwater (maps, cross-sections, time trends) • CoC concentrations in internal sinks such as pumping wells, seeps or springs (time trends) • CoC mass loading to internal sinks (e.g. wells, drains) or surface water (streams, lakes) h) the sensitivity/uncertainty analysis approach and outcomes (Note; this aspect is critical since calibration of transport model is often not feasible).
8	Model Predictions	Present the model predictions in response to the resource management options simulated, including: a) Predicted changes in groundwater flow system (e.g. maps, cross-sections of heads/drawdown, hydrographs of mine inflow etc.) b) Predicted contaminant transport (e.g. contour plans of contaminant plumes, breakthrough curves at compliance points, mass loading vs. time, etc.) Assess the influence of model uncertainty on predicted groundwater flow and/or contaminant transport.
9	Model limitations	Describe and discuss the uncertainties in relation to the conceptual model, and model calibration and prediction simulations, and possible methods of resolving them by subsequent data acquisition, field monitoring, further analysis and/or modelling, and resolution by future construction of mitigative measures.

Item	**Title**	**Detail** (as relevant for the objectives and complexity)
10	Conclusions and Recommendations	Summarize the preferred management scenario, and other study findings. Provide conclusions about the potential impact of natural resource development (or alternative scenarios) on the groundwater system and associated surface water (streams, lakes) w/ acknowledgment of model uncertainty. Recommend management plans and future work programs (e.g. additional field work, modelling etc.).
11	References	List references of relevant literature. Consider a summary (possibly in the form of an annotated bibliography) of the key reference papers and reports.
12	Appendices	Especially for a medium- or high-complexity model, it is recommended that much of the detailed information (e.g. summary sheets of model output for calibration, sensitivity analysis and prediction) be presented in Appendices in graphical and tabular form. This allows for the body of the report to be written in a lucid style for easy communication of the approaches used and issues addressed.

10.4.3 *Final Report for Predictive Model*

A report on a predictive model should generally follow the guidelines above for a report on a conceptual model. In addition, a report on a predictive model may include the following:

- Description of the baseline conceptual model that is the basis of the predictive model
- Details of the mine project and works that give rise to the need for a predictive model
- Description of the predictive model
- Discussion of how the predictive model is derived from, based on, or deviates from the conceptual model
- Plans for monitoring the groundwater to ascertain if and how the new mine works are affecting groundwater
- A description of mitigative measures that may be implemented if monitoring indicates a significant deviation from model predicted conditions

10.5 MONITORING PLANS

If the report on the conceptual baseline model and/or the report on a predictive model recommends additional and/or ongoing monitoring, details of the monitoring should be included in the model report or in a separate, stand-alone monitoring report. At the very least, a monitoring report (plan) and/or sections of a model report dealing with monitoring, should include the following:

- Reasons for proposed monitoring or data gathering.
- Description of monitoring facilities
- Standard procedures for using (measuring) the monitoring facilities
- Schedules for preparation and submission of reports on the monitoring to regulators
- Measured trigger levels that may give rise to a need for installation of mitigative measure or the need to undertake remedial work. A trigger level is the value of a measured parameter that may be compared to the value of the parameter as predicted by a model.

10.6 MODEL REVIEW

Peer reviews should be documented. A typical peer review report may include descriptions and discussion of the following:

- Model objectives
- The adequacy of the conceptual model
- The adequacy of the mathematical model
- Calibration sufficiency
- Predictive models reasonableness
- Sufficiency of the uncertainty analysis

10.7 QA/QC

QA/QC procedures and implementation should be documented. The QA/QC documentation may include descriptions of:

- Checks on datasets used for model inputs. Data entry or interpretation errors can be identified.
- Checks on model construction. Construction and application of the mathematical model can be verified. For example, boundary conditions can be checked for entry errors, model grids can be checked for holes or areas of unintended high density, and verification that calibration points are input and used correctly.
- Checks on model results. Results should be checked for plausibility. Often, during review of model results, model setup errors can be identified that were overlooked during model construction. Checks can include model mass balance, water table contours and hydraulic head measurements. Maps or figures of model results can be used to assess spatial variability in model results or identify possible boundary condition errors.

10.8 MODEL ARCHIVE DOCUMENTATION

Model archive documentation need not by submitted by the proponent to the regulator. Proponents should recognize however, that in the event of litigation, such documentation is discoverable and should accordingly be prepared to a high standard and kept safe for future reference.

Model datasets and results files should be archived in a way to allow ease of access at later dates. Proper archiving of key modelling input/output files can be important for (i) future follow-up work and/or (ii) potential review during a modelling audit.

It is good practice to use a model journal. Such a journal can provide both a record of what has been completed and a tracking method to locate appropriate files at a future date, if necessary. The journal should be used as a method to track the progression of the modelling process. As such, it is useful to keep concise notes on how the process evolved, inputs received or generated, and model output files.

A good record of model runs, which should be named in a logical manner, provides a useful resource when addressing questions or determining the cause for surprising or incorrect results. This is particularly important during the calibration and uncertainty analysis phases, but also important at other phases. The journal should include file names and locations of datasets, model inputs and model output files.

11 MODEL REVIEW

11.1 INTRODUCTION

11.1.1 General

This section describes the types and phases of review of a groundwater model to be undertaken by or on behalf of the British Columbian (or other) regulatory authorities.

Generally the reviews described in this section are undertaken by regulatory staff on receipt of reports that describe the project and relevant groundwater modelling as submitted by the proponent.

11.1.2 Types of Review

The following categories of groundwater model review that may be undertaken are described in detail in this section:

- Model appraisal
- Peer review
- Model audit
- Post-audit.

Figure 11-1 shows a flow chart that illustrates the sequence and circumstances in which one or more of the following groundwater model reviews may be undertaken in the context of an EA application.

11.1.3 Topics Not Covered

This section does not address review of groundwater models by the proponent (or their consultants) that are (or should) be undertaken during preparation of the model and before submission to the regulatory authority. It is recommended, however, that the review guidelines and checklists in this section be considered by the proponent (or their consultant) in undertaking review prior to submittal of the model to the regulatory authority.

11.2 MODEL APPRAISAL (REVIEW)

11.2.1 Description

A model appraisal review is undertaken to establish that the model conforms with standard modelling practices (as described in these guidelines). Specifically a model review focuses on:

- The adequacy of field data
- The plausibility of modelling assumptions
- The adequacy of model calibration and sensitivity analysis
- The adequacy of consideration of model uncertainty/limitations
- The plausibility of model predictions
- The completeness of documentation.

A detailed assessment of the numerical aspects of the groundwater modelling study is usually not included in this type of review.

11.2.2 Projects Requiring Model Appraisal

Groundwater modelling projects submitted by a proponent to the regulator are subjected to a model appraisal by qualified staff from the regulatory authorities (Figure 11-1). This includes, but is not limited to, projects in which groundwater modelling is required to assess the environmental impact of a natural resource project and/or the efficacy of mitigative/remedial action.

11.2.3 Reviewer Qualifications

Model appraisals may be undertaken by a professional person with training in hydrogeology. Experience in numerical modelling is preferred, but not mandatory.

11.2.4 Content of Model Appraisal

11.2.4.1 Key Questions

The appraiser should ask at least the following key questions:

- What are the primary questions of the modelling study and the overall modelling objectives?
- Does the model address the stated modelling objectives, i.e.:
    - What key physical processes should be included in the model to meet the objectives?
    - Does the selected model include the ability to model these processes?
    - Is there enough information to quantify these processes?
- What site characterization studies/data are used to build the conceptual model?
- Are available data reliable and representative of site conditions?
- What are key data gaps?
- Does the site conceptual model represent a reasonable (simplified) representation of actual field conditions?
- What are the key modelling assumptions used to define the conceptual model and hence to compile the numerical model?
- Are the assumptions appropriate and justified?
- What are the potential implications of improper assumptions or data gaps?
- Does the model study apply sound and accepted modelling practices (these guidelines)?
- Are the model predictions consistent and plausible with available knowledge about the site?
- Are model limitations and model uncertainties adequately addressed?

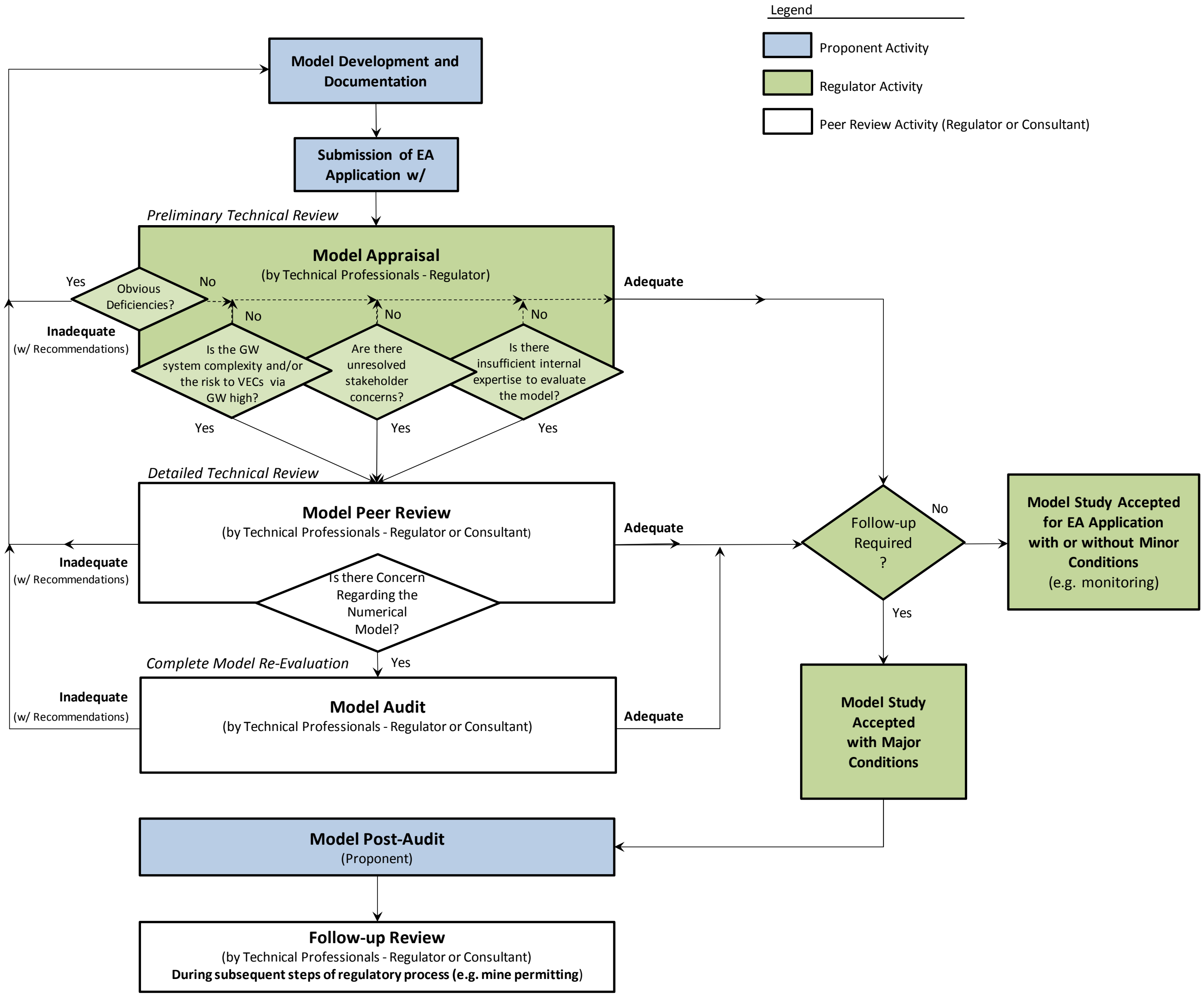


Figure 11-1: Groundwater model review process

11.2.4.2 Appraisal Checklists

Checklists for documenting a model appraisal are provided in Table D1 in Appendix D. The checklists are intended to assist the appraiser in reviewing proponent submittals and reporting on findings. The checklists are not necessarily exhaustive; appraisers are encouraged to expand or adapt the checklists to the specifics of each project.

The checklist includes questions regarding model:

(1) Reporting
(2) Data collection & analysis
(3) Model conceptualization
(4) Model design
(5) Calibration
(6) Validation
(7) Prediction
(8) Sensitivity/uncertainty analysis.

The checklist includes questions related to groundwater flow and contaminant transport. The applicability of a question depends on the modelling objectives and model complexity. For example, questions on contaminant transport modelling are not applicable to a groundwater resource project where contaminant transport is not a concern.

For each question in the checklist, the appraiser should note which of the following answers best describes the model:

- NOT APPLICABLE
- MISSING
- DEFICIENT
- ADEQUATE.

To facilitate the completion of the checklist, the appraiser only needs to place a check mark in the appropriate column provided on the checklist. Note that questions of the Yes/No type either fall under the category of “MISSING” or “ADEQUATE” (depending on the question posed) unless the question is NOT APPLICABLE.

Note that many questions on the check lists require judgment on part of the reviewer. The reviewer should provide additional comments to justify these more subjective answers either on the check lists and/or in an accompanying report (see below). In particular, any aspects of the model study judged to be “DEFICIENT” should be justified.

To flag serious model deficiencies, a second checklist has been designed for Model Compliance (see Table D2 in Appendix D). This checklist consists of a list of questions with a PASS or FAIL response. The reviewer may use this checklist to highlight corrective action which should be undertaken before the model is deemed acceptable.

11.2.4.3 Appraisal Report

A report shall be prepared by the appraiser on the findings of the model review. Depending on the nature and scope of the project, the groundwater modelling, and the appraiser's findings, the report may consist of one or more of the following:

- ➢ Checklists and a covering memorandum noting that the review has been undertaken in accordance with these guidelines and is reported via the checklists. The memorandum should note whether the proponent's submittals are approved, rejected, or returned with comments and request for additional work.
- ➢ A stand-alone appraisal document that elaborates on findings with a special emphasis on potential deficiencies of the model study (i.e. MISSING or DEFICIENT) and their implications for the environmental assessment of the proposed project. A completed appraisal checklist should be appended to the appraisal document.

11.3 PEER REVIEW

11.3.1 Description

The peer review may be undertaken by regulatory staff pursuant to (or sometimes in parallel with) a model appraisal (Figure 11-1). A peer review involves a more in-depth review of the model study with special emphasis on the numerical aspects of the model study.

If the proponent has undertaken a peer review of the groundwater model prior to submission of the work-product to the regulator, the proponent is encouraged to include the peer review report with the submission.

11.3.2 Projects Requiring Peer Review

A peer review should be considered if any of the following criteria are met (Figure 11-1):

(i) The project is close to high-value VECs (e.g. fish-bearing streams or lakes) and there is a potential for significant environmental impact via the groundwater pathway and groundwater modelling is required to assess the degree of impact and/or the efficacy of mitigation measures and/or remedial actions
(ii) The groundwater system and/or the groundwater model are very complex requiring special expertise/training not covered by the regulatory staff completing the appraisal
(iii) Model appraisal(s) from different regulatory agencies are contradictory.

In special circumstances, particularly for complex modelling projects in which significant risk(s) to VECs are anticipated, it may be advantageous for parties involved to conduct a peer review progressively throughout the modelling process. Such a progressive peer review is not mandatory and the terms and conditions for this peer review would have to be negotiated between the Proponent and the regulatory agencies.

11.3.3 Reviewer Qualifications

11.3.3.1 Individual Attributes

Peer reviewers should have expert knowledge in groundwater modelling. Attributes to consider when selecting a peer reviewer include:

- Years of experience
- Local hydrogeological knowledge
- Modelling track record (as a developer or team leader)
- Familiarity with relevant software packages (e.g. analytical models, finite differences, finite elements)
- Familiarity with the modelling application under consideration (unsaturated zone, saturated flow, solute transport, density effects)
- Awareness of non-uniqueness in parameter estimation; and familiarity with the potential for numerical errors (solvers, deformed grids, re-wetting)
- No conflict of interest for the project.

11.3.3.2 Internal vs. External Review

A peer review may be completed by qualified staff from the regulatory agency (“in-house”) or by an outside specialist (e.g. consultant or academic) contracted by the agency. The former case is referred to as an “internal peer review” whereas the latter is referred to as an “external peer review”.

11.3.3.3 Neutral-Party Review

The regulatory agency and the proponent may agree, in specific instances, to hire a “neutral” (and qualified) reviewer who is specifically instructed to perform the peer review at “arm’s length” of both parties. This is referred to as an “independent third-party review”.

11.3.3.4 Teams

For a complex study, a team of reviewers might be required to address a range of topics and technologies. For example, additional team peer reviewers may be required in these disciplines: geology, hydrogeology, geochemistry, and/or specialist numerical modelling.

11.3.4 Content of Peer Review

11.3.4.1 Key Questions

The peer review is a more comprehensive review than the model appraisal with special emphasis on the numerical aspects of the model study. The peer review should cover all key questions listed above for the model appraiser plus the following additional questions related to the numerical aspects of the study:

- Is the modelling scope and selected modelling code adequate for the study objectives?
- Does setup of the numerical model follow sound and accepted modelling practices?
- Does calibration of the numerical model follow sound and accepted modelling practices?
- Does the scope of sensitivity and scenario analyses cover the uncertainty in model input parameters and the conceptual model?
- Are numerical methods and assumptions adequately documented and justified?
- Are the numerical methods adequate and do not bias model predictions and conclusions?
- Are limitations in the numerical modelling approach discussed and their influence on model predictions evaluated?

11.3.4.2 Checklists

While each peer reviewer has their own approach to conducting a review, it is recommended that the standardized approach (using a checklist with eight main categories) be used to complete a peer review.

The full checklist for a peer review is presented in Table D3 of Appendix D. The checklist for the peer review covers questions posed in the more general model appraisal (see Table D1) but also includes more in-depth questions on the modelling study.

The checklist is designed for highly complex models. For models with lower complexity, the reviewer must be conscious that some questions will be NOT APPLICABLE and need not be addressed.

The primary purpose of the detailed peer review checklist is to serve as a systematic evaluation tool which can guide the reviewer's assessment, and ensure fair treatment and consistency across different reviews. The checklist should serve as a basis for (but does not replace) a detailed peer review report in which the reviewer outlines the detailed findings of the model review.

11.3.4.3 Report

The scope and format of a peer review report depends on the scope of the peer review which can vary greatly from project to project. Hence specific guidelines are not mandated about the content and/or structure of the peer review report. It is recommended, however, that the scope of the peer review and the final report be clearly stated at the outset of the peer review. The scope of work for a peer review should also specify whether a formal check is included and, if so, whether the completed check list will be disclosed to the proponent (or their modelling consultant).

11.4 MODEL AUDIT

11.4.1 Description

The following are guidelines for a model audit by the regulator.

A model audit is an in-depth review of the numerical model, including an inspection of data input and data output files to ensure that the model has no errors. A model audit is similar to Quality Control/Quality Assurance (QA/QC) typically performed for engineering calculations and designs in the consulting industry. The proponent is encouraged to submit QA/QC documentation and/or model audits of their work product to the regulator. Doing so may obviate the need for a model audit by the regulator.

11.4.2 Projects Requiring Model Audit

It is recommended that model audits only be considered by regulatory agencies for review of very complex modelling studies where an earlier peer review had indicated potential problems with the numerical model and has recommended the completion of a model audit.

11.4.3 Reviewer Qualifications

A model audit should be done by a hydrogeologist with experience in groundwater modelling (similar to that of a peer reviewer), with specific expertise in the software code used for the modelling study in question.

The model audit may be completed by the peer reviewer recommending the audit or by another individual appointed by the regulatory agency.

The model auditor requires access to the modelling software(s) used for the modelling study.

11.4.4 Content of Model Audit

11.4.4.1 General

The audit includes an in-depth review of the model data files, simulations, and outputs.

Data files for at least one representative simulation should be provided to the auditor so that he/she can verify that the model structure is as reported and runs successfully without numerical errors or mass imbalances.

The construction of a model using a graphical user interface (GUI) facilitates a model audit. The auditor should proceed systematically through each GUI menu to check that the digital representation of the model matches the information provided in the report. The auditor should check that all processes identified in the conceptual model are in fact activated and populated with data.

11.4.4.2 Checklists

The model audit requires an in-depth check of the consistency between reported and actual model input. No formal checklists have been prepared for this type of review; however, the model auditor is encouraged to develop a project-specific checklist for a model audit. Tables or figures showing the range of reported parameter values should be included in such a check list.

It is not possible to present in a model report the full detail of a model – particularly the spatial distributions of aquifer properties and layer elevations, and the temporal distributions of applied stresses. The auditor should pay particular attention to unreported features of the model. The auditor should scrutinize the settings of switches or options in model packages or process algorithms, water balance and a visual check of the numerical solution (some software errors exist in all packages and GUIs) to ensure that the process is being simulated in the manner intended by the modeller.

11.4.4.3 Report

A report on the model audit should be prepared. The scope should include:

- Description of report(s) and model(s)
- Model input files reviewed
- Model output files reviewed
- Model simulation checks undertaken as part of the audit.
- Findings
- Recommendations.

11.5 POST-AUDIT

11.5.1 Description

A post-audit describes the process of revisiting the groundwater model sometime (often years) after it is completed to assess the accuracy of model predictions. A groundwater model prepared before project implementation is always predictive. Once the project starts, monitoring of groundwater conditions is normally undertaken. A post-audit consists of comparing post-start-up monitoring data to the predictions of the pre-start-up model. If there is a significant difference between predicted and measured parameters, it may be necessary and appropriate to recalibrate the model and rerun the model to predict future groundwater performance.

This is essentially an alternative method of model verification, or assessment of model uncertainty. It requires the collection of additional field data (for example, drawdown in response of pit dewatering) which are not available at the time of the modelling study.

A post-audit may be requested by the regulatory agencies (based on a model appraisal or peer review) but should be conducted by the developer (see Figure 11-1).

11.5.2 Projects Requiring Post-Audit

As part of the approval of a groundwater model and permitting of the start of a project, the regulator may require that the proponent (Figure 11-1):

- Undertake specified groundwater monitoring.
- Compare model-predicted to monitored groundwater conditions.
- Recalibrate the groundwater model to achieve a better fit between predicted and monitored conditions.
- Rerun the model in predictive mode to establish future groundwater performance.

In the EA process, a formal model post-audit may be required if there is significant risk of adverse impacts to VECs via a groundwater pathway and there is significant uncertainty in model predictions. A post-audit of a groundwater model may be requested by the regulatory agency conducting the model appraisal or the peer review (Figure 11-1).

If warranted, the regulatory agency in charge of the EA application (i.e. EAO) may request a model post-audit as a condition in the EA certificate.

11.5.3 Content of Post-Audit

11.5.3.1 General

Development of a natural resource (in particular a large mining projects) may take many years. The following are examples of times when a groundwater model, which was developed and calibrated for the EA process using pre-mining conditions, could be post-audited:

- Once initial mine dewatering has commenced.
- At start-up of mining (e.g. pit excavation, tailings discharge).
- Change in mine plan (say new open pit or TSF).
- Mine closure activities (e.g. cessation of mine dewatering, cover placement etc.).

The actual mine plan (or groundwater extraction plan) implemented may have changed significantly from the plan simulated in the original modelling study (e.g. at the EA level). As a result, a post-audit requires, at a minimum, adjustment of those stresses in the original model.

In cases where additional data collection (e.g. additional drilling, testing) indicate significant discrepancies with the original model, significant changes to the conceptual model and hence numerical model may also be required during the post-audit.

The practice of post-auditing adds significant overall value to the modelling project by using the model in management mode (i.e. continual development with new data), rather than just crisis mode (i.e. to “answer” a question and then shelve the model).

A successful post-audit (i.e. good match of predicted and observed response) provides a high degree of confidence in the predictive capability of the model. An unsuccessful post-audit (i.e. poor match) is still valuable as it provides information on how to improve the model.

11.5.3.2 Reporting of a Post-Audit

The results of a post-audit should be summarized in a report by the Proponent and submitted to the regulatory agency requesting the post-audit.

The scope of the post-audit report depends on the scope of the post-audit. At a minimum, the post-audit report should describe the scope of the post-audit (i.e. new modelling period and stresses simulated), numerical methods used and the findings of the post-audit. If significant changes to the groundwater model were required to obtain an adequate match with observations than a comprehensive modelling report, including results of updated predictions and uncertainty analysis (see section 10) should be submitted to the regulatory agency that requested the post-audit.

11.5.4 Review of Post-Audit

Submission of a post-audit report will trigger a new round of review by the regulator or their appointed representative (consultant, academic) (Figure 11-1).

The review of the post-audit document may be undertaken in accordance with the procedures for a model appraisal and/or a peer review. The qualifications of the regulatory staff (or representative) conducting this review should be as listed above for the specific review activity.

SUMMARY POINTS FOR MODEL REVIEW

1. A model appraisal review is undertaken to establish that the model conforms to standard modelling practices (as described in these guidelines).
2. A peer review involves a more in-depth review of the model study with special emphasis on the numerical aspects of the model study. In special circumstances, particularly for complex modelling projects in which significant risk(s) to VECs are anticipated, it may be advantageous for all parties involved to conduct a peer review progressively throughout the modelling process.
3. A model audit is an in-depth review of the numerical model, including an inspection of data input and data output files to ensure that the model has no errors. It is recommended that model audits only be considered by regulatory authorities for review of very complex modelling studies where an earlier peer review had indicated potential problems with the numerical model and had recommended the completion of a model audit.
4. A post-audit describes the process of revisiting the groundwater model sometime (often years) after it is completed to assess the accuracy of model predictions. A post-audit consists of comparing post-start-up monitoring data to the predictions of the pre-start-up model. If there is a significant difference between predicted and measured parameters, it may be necessary and appropriate to recalibrate the model and rerun the model to predict future groundwater performance.
5. Documentation of the review process and reporting of the results is a key component of a model review at any level.
6. The model review checklists provided in Appendix D serve as a systematic evaluation tool which can guide the reviewer’s assessment, and ensure fair treatment and consistency across different reviews.

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GLOSSARY OF GROUNDWATER AND GROUNDWATER MODELLING TERMS

Compiled from: **MDBC, 2001**

NZMoE, 2001

USGS (http://or.water.usgs.gov/projs_dir/willgw/glossary.html)

USEPA (http://water.epa.gov/drink/resources/glossary.cfm)

Entry	Acronym	Primary Definition
A		
Absorption		The process by which substances in gaseous, liquid or solid form dissolve or mix with other substances (ASCE, 1985).
Accuracy		How closely a model predicts the true or actual value of the variable being simulated.
Acid Mine Drainage	AMD (see also ARD)	Drainage of water from areas that have been mined mineral ores; the water has low pH, sometimes less than 2.0 (is acid), because of its contact with sulfur-bearing material; acid drainage is harmful because it often kills aquatic organisms.
Acidic		The condition of water or soil which contains a sufficient amount of acid substances to lower the pH below 7.0.
Acid Rock Drainage	ARD (see also AMD)	See Acid Mine Drainage
Adsorption		Adherence of gas molecules, ions, or molecules in solution to the surface of solids (ASCE, 1985).
Adsorption isotherm		The graphical representation of the relationship between the solute concentration and the mass of the solute species adsorbed on the sediment or rock
Advection		Advection - The process whereby solutes are transported by the bulk mass of flowing fluid (Freeze and Cherry, 1979). See also convective transport.
Aerobic		A condition in which free (atmospheric) or dissolved oxygen is present in the water.

Entry	Acronym	Primary Definition
Aggregate		A mass or cluster of soil particles, often having a characteristic shape.
Air-space-ratio		The ratio of (a) the volume of water that can be drained from a saturated soil or rock under the action of force of gravity to (b) the total volume of voids (ASTM, 1980).
Alluvium		Sediments (clays, sands, gravels and other materials) deposited by flowing water. Deposits can be made by streams on river beds, floodplains, and alluvial fans.
Analytical Model		Equations that represent exact solutions to the hydraulic equation for one- or two-dimensional flow problems under broad simplifying assumptions, usually including aquifer homogeneity. They can be solved by hand, or by simple computer programs (e.g.. WinFlow, TwoDan), but do not allow for spatial or temporal variability. They are useful to provide rough estimations for many applications with little effort, as they usually do not involve calibration (site
Anisotropy		The condition of having different properties in different directions (AGI, 1980).
Anaerobic		A condition in which "free" (atmospheric) or dissolved oxygen is NOT present in water.
Anisotropic		A mass having different properties in different directions at any given point (ASTM, 1980).
Apparent Groundwater velocity		See specific discharge.
Aquatic		Plants or animal life living in, growing in, or adapted to water.
Aquiclude		A hydrogeologic unit which, although porous and capable of storing water, does not transmit it at rates sufficient to furnish an appreciable supply for a well or spring (after WMO, 1974). See preferred term confining unit.

Entry	Acronym	Primary Definition
Aquifer		(1) A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (after Lohman and others, 1972). (2) A geologic formation, group of formations, or part of a formation capable of yielding a significant amount of groundwater to wells or springs. Any saturated zone created by uranium or thorium recovery operations would not be considered an aquifer unless the zone is or potentially is (1) hydraulically interconnected to a natural aquifer, (2) capable of discharge to surface water, or (3) reasonably accessible because of migration beyond the vertical projection of the boundary of the land transferred for long-term government ownership and care (10 CFR Part 40 Appendix A). (3) A formation, a group of formations, or a part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (10 CFR Part 960.2). (4) A zone, stratum, or groups of strata that can store or transmit water in sufficient quantities for a specific use (30 CFR Part 710.5). (5) Geological formation, groups of formations, or part of a formation, that is capable of yielding a significant amount of water to a well or spring (40 CFR Parts 146.03; 260.10; 270.2). (6) A geologic formation, group of formations, or portion of a formation capable of yielding usable quantities of groundwater to wells or springs (40 CFR Part 257.3-4).
Aquifer, confined		An aquifer that is overlain by a confining bed. The hydraulic conductivity of the confining bed is significantly lower than that of the aquifer.
Aquifer, perched		A region in the unsaturated zone where the soil may be locally saturated because it overlies a low permeability unit.
Aquifer, semiconfined		An aquifer confined by a low-permeability layer that permits water to slowly flow through it. During pumping of the aquifer, recharge to the aquifer can occur across the confining layer. Also known as a leaky artesian or leaky confined aquifer.

Entry	Acronym	Primary Definition
Aquifer, unconfined		Also known as water-table or phreatic aquifer. An aquifer in which there are no confining beds between the zone of saturation and the surface. The water table is the upper boundary of unconfined aquifers.
Aquifer system		A body of permeable and poorly permeable material that functions regionally as a water-yielding unit; it comprises two or more permeable beds separated at least locally by confining beds that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system; includes both saturated and unsaturated parts of permeable material (after ASCE, 1985).
Aquifer test		A test to determine hydrologic properties of the aquifer involving the withdrawal of measured quantities of water from or addition of water to a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or additions (ASCE, 1985).
Aquifuge		(1) A hydrogeologic unit which has no interconnected openings and, hence cannot store or transmit water (after WMO, 1974).
Aquitard		A confining bed that retards but does not prevent the flow of water to or from an adjacent aquifer; a leaky confining bed. It does not readily yield water to wells or springs, but may serve as a storage unit for ground water (AGI, 1980). See preferred term confining unit.
Area of influence		The area surrounding a pumping or recharging well within which the potentiometric surface has been changed (after ASCE, 1985).
Artesian		Synonymous with confined (Lohman and others, 1972).
Artesian aquifer		Synonymous with confined aquifer (ASCE, 1985).

Entry	Acronym	Primary Definition
Artesian well		A well deriving its water from an artesian or confined aquifer (after ASCE, 1985).
Artificial recharge		Recharge at a rate greater than natural, resulting from deliberate or incidental human activities (WRC, 1980).
Average interstitial velocity		Average interstitial velocity - See velocity, average interstitial.
B		
Base flow		That part of the stream discharge that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by groundwater discharge (after APHA, 1981).
Baseflow recession		The declining rate of discharge of a stream fed only by baseflow for an extended period. Typically, a baseflow recession will be exponential.
Baseline model		A model which seeks to replicate the current conditions.
Baseline monitoring		The establishment and operation of a designed surveillance system for continuous or periodic measurements and recording of existing and changing conditions that will be compared with future observations (after NRC, 1982).
Bedrock		The solid, unweathered rock that lies beneath the loose surface deposits of soil, alluvium, etc.
Best management practices		Structural, nonstructural and managerial techniques that are recognized to be the most effective and practical means to control nonpoint source pollutants yet are compatible with the productive use of the resource to which they are applied. BMPs are used in both urban and agricultural areas.
Biodegradation, aerobic		Decomposition of organic matter by microorganisms in the presence of free oxygen. The decomposition end-products are carbon dioxide and water.

Entry	Acronym	Primary Definition
Biodegradation, anaerobic		Decomposition of organic matter by microorganisms in the absence of free oxygen. Other electron acceptors, other than oxygen, are used by bacteria in this decomposition process. The decomposition end-products are enriched in carbon.
Breakthrough curve		A plot of relative concentration versus time, where relative concentration is defined as C/Co with C as the concentration at a point in the groundwater flow domain, and Co as the source concentration.
Bore (well)		A structure drilled or dug below the surface to obtain water from an aquifer.
Boundary condition		A mathematical statement specifying the dependent variable (e.g. hydraulic conductivity or concentration) at the boundaries of the modeled domain which contain the equations of the mathematical model. Examples are Specified Head, Specified Concentration, Specified Flux (flow or mass flux), or Mixed Boundaries.
Boundary condition (Type 1)		Specified Head: Refer to Dirichlet Condition (First Type Boundary)
Boundary condition (Type 2)		Specified Flow: Refer to Neumann Condition (Second Type Boundary)
Boundary condition (Type 3)		Head-dependent Flow: Refer to Cauchy Condition (Third Type Boundary)
Buildup		The vertical distance the water table or potentiometric surface is raised, or the increase of the pressure head due to the addition of water.
C		
Calibration		The process by which the independent variables (parameters) of a numerical model are adjusted, within realistic limits, to produce the best match between simulated and observed data (usually water-level values). This process involves refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve the desired degree of correspondence between the model simulations and observations of the groundwater flow system.

Entry	Acronym	Primary Definition
Calibration, Intial Conditions		The initial hydrologic conditions for a flow system that are represented by its aquifer head distribution at some particular time corresponding to the antecedent hydrologic conditions in that system. Initial conditions provide a starting point for transient simulations.
Calibration, Steady State		The calibration of a model to a set of hydrologic conditions that represent (approximately) an equilibrium condition, with no accounting for aquifer storage changes.
Calibration, Transient or Dynamic		The calibration of a model to hydrologic conditions that vary dynamically with time, including consideration of aquifer storage changes in the mathematical model.
Calibration target		Measured (observed) values used in the calibration process. May include static or dynamic water levels, surface water discharge, seep survey data, etc.
Capillary action		The movement of water in the interstices of a porous medium due to capillary forces (after ASTM, 1980).
Capillary conductivity		(1) The property of an unsaturated porous medium to transmit liquid (after AGI, 1980).
Capillary fringe		The lower subdivision of the unsaturated zone immediately above the water table in which the interstices are filled with water under pressure less than that of the atmosphere, being continuous with the water below the water table but held above it by capillary forces (after ASCE, 1985).
Capillary head		The potential, expressed in head of water that causes the water to flow by capillary action (ASTM, 1980).
Capillary water		(1) Water held in the soil above the phreatic surface by capillary forces.

Entry	Acronym	Primary Definition
Cascading water		In reference to wells, groundwater that trickles or pours through cracks or perforations down the casing or uncased borehole above the water level in the well (after Wilson, 1980).
Cauchy Condition		Also known as Head-dependent Flow or Third Type Boundary Condition. A boundary for a groundwater model where the relationship between the head and the flow at a boundary is specified, and the model computes the groundwater flux for the head conditions applying.
Cell		Also called element, a distinct two-dimensional or three-dimensional model unit representing a discrete portion of a physical system with uniform properties assigned to it.
Code selection		The process of choosing the appropriate computer code, algorithm, or other analysis technique capable of simulating those characteristics of the physical system required to fulfill the modelling objective(s).
Complexity		The degree to which a model application resembles, or is designed to resemble, the physical hydrogeological system (adapted from the model fidelity definition given in Ritchey and Rumbaugh, 1996). A hierarchical classification of three main complexities in order of increasing complexity: Basic, Impact Assessment, and Aquifer Simulator. Higher complexity models have a capability to provide for more complex simulations of hydrogeological process and/or address resource management issues more comprehensively.
Complexity, Basic Model		With limited data availability and status of hydrogeological understanding, and possibly limited budgets, a Basic model could be suitable for preliminary quantitative assessment (rough calculations), or to guide a field programme.
Complexity, Impact Assessment Model		More detailed assessments are possible with an Impact Assessment approach, which usually requires more data, better understanding, and greater resources for the study.

Entry	Acronym	Primary Definition
Complexity, Aquifer Simulator		An Aquifer Simulator is a high complexity representation of the groundwater system, suitable for predicting the response of a system to arbitrary changes in hydrogeological conditions.
Comprehensive Scenario Analysis		A sensitivity analysis approach where the results from performing a wide ranging set of model simulation scenarios are assessed to show likely ranges in aquifer response (however, this approach does not quantify the likelihood of each possible outcome, which requires a stochastic or Monte Carlo analysis).
Computer code		(Computer program) The assembly of numerical techniques, bookkeeping, and control language that represents the model from acceptance of input data and instruction to delivery of output. Examples: MODFLOW, FEFLOW, MT3D, etc.
Concentration gradient		The change in solute concentration per unit distance in solute. Concentration gradients cause Fickian diffusion (spreading) of solutes from regions of highest to regions of lowest concentrations. In slow moving groundwater, this is the dominant mixing process.
Conceptualization error		A modelling error where model formulation is based on incorrect or insufficient understanding of the modeled system.
Conceptual model		A simplified and idealized representation (usually graphical) of the physical hydrogeologic setting and our hydrogeological understanding of the essential flow processes of the system. This includes the identification and description of the geologic and hydrologic framework, media type, hydraulic properties, sources and sinks, and important aquifer flow and surface-groundwater interactions.
Cone of depression		A depression of the potentiometric surface in the shape of an inverted cone that develops around a well which is being pumped (after ASCE, 1985).
Cone of influence		The depression, roughly conical in shape, produced in the water table by the pumping of water from a well.
Cone of impression		A rise of the potentiometric surface in the shape of a cone that develops around an injection well.

Entry	Acronym	Primary Definition
Confined		A modifier which describes a condition in which the potentiometric surface is above the top of the aquifer.
Confined aquifer		An aquifer in which ground water is confined under pressure which is significantly greater than atmospheric pressure.
Confining bed		A body of impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers (40 CFR 146.3).
Confining Layer		A body of relatively impermeable material that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer.
Confining unit		A hydrogeologic unit of impermeable or distinctly less permeable material bounding one or more aquifers and is a general term that replaces aquitard, aquifuge, aquiclude (after AGI, 1980). See definition 2, confining bed.
Conjunctive use		The combination of surface water and groundwater storage to optimize total available water resources.
Connate water		Water entrapped in the interstices of a sedimentary or extrusive igneous rock at the time of its deposition (AGI, 1980).
Constand-head node		A location in the discretized groundwater flow model domain (node) where the hydraulic head remains the same over the time period considered.
Contaminant		Any physical, chemical, biological, or radiological substance or matter that has an adverse effect on air, water, or soil.
Contaminant fate		Chemical changes and reactions that change the chemical nature of the contaminant as it moves through the groundwater system.
Contaminant of Concern	CoC	A chemical species identified in a groundwater system that poses a risk to the environment and which must be held to specified standards.

Entry	Acronym	Primary Definition
Contaminant Transport model		A model describing the movement of contaminants in the environment.
Contaminant Transport velocity		The rate at which a contaminant move through an aquifer.
Contamination		The addition to water of any substance or property preventing the use or reducing the usability of the water (AGI, 1980). Sometimes considered synonymous with pollution. Contaminant plume - An elongated body of groundwater containing contaminants, emanating and migrating from a point source within a hydrogeologic unit(s).
Contaminate		To introduce a substance that would cause: (1) The concentration of that substance in the groundwater to exceed the maximum contaminant levels, or (2) An increase in the concentration of that substance in the ground water where the existing concentration of that substance exceeds the maximum contaminant levels (40 CFR 257.3-4).
Contour line		see Equipotential line
Convective diffusion		See Mechanical dispersion, coefficient.
Convective transport		The component of movement of heat or mass induced by thermal gradients in groundwater.
Convection		The process whereby heat is carried along with the flowing groundwater (after Freeze and Cherry, 1979).
Courant criteria		In solute transport modelling, the product of the advective time step multiplied by the advective velocity divided by the characteristic distance between nodes should not exceed a value of 1 (C < 1) so that numerical dispersivity is minimized. In other words, the advective time step should be chosen so that it is less than the time is takes the solute to advect between nodes.
Cumulative Distribution Factor	CDF	A graph or formula that expresses the probability that an uncertain parameter will be less than or equal to a particular value.
D		

Entry	Acronym	Primary Definition
Darcian velocity		Darcian velocity - See specific discharge.
Darcy's Law		An empirical law which states that the velocity of flow through d porous medium is directly proportional to the hydraulic gradient assuming that the flow is laminar and inertia can be neglected (after Darcy, 1856).
Degradation constant		Term used to address the decay of contaminant concentration due to factors other than dispersion.
Degree of saturation		See percent saturation.
Density		The mass or quantity of a substance per unit volume. Units are kilograms per cubic metre of grams per cubic centimetre.
Desorption		The reverse process of sorption.
Deterministic		A description of a parameter or a process with uniquely defined qualities. A deterministic parameter has, or is assumed to have, a unique value of a unique spatial distribution. The outcome of a deterministic process is known with certainty. There is, or is assumed to be, a clear cause-and-effect relation between independent and dependent variables.
Differential water capacity		The absolute value of the rate of change of water content with soil water pressure. The water capacity at a given water content will depend on the particular desorption or adsorption curve employed. Distinction should be made between volumetric and specific water capacity (SSSA, 1975).
Diffusion		Process whereby ionic or molecular constituents move under the influence of their kinetic activity in the direction of their concentration gradient (Freeze and Cherry, 1979). Diffusion coefficient - See molecular diffusion, coefficient.
Diffusion coefficient		A constant or proportionality which related the mass flux of a solute to the solute concentration gradient.

Entry	Acronym	Primary Definition
Diffusion, convective		See mechanical dispersion, coefficient.
Diffusivity		The hydraulic conductivity divided by the differential water capacity (care being taken to be consistent with units), or the flux of water per unit gradient of moisture content in the absence of other force fields (SSSA, 1975).
Dirichlet Condition		Also known as a Specified, Fixed, or Constant Head Boundary, or Third Type Boundary Condition. A boundary condition for a groundwater model where the head is known and specified at the boundary of the flow field, and the model computes the associated groundwater flow.
Discharge		The volume of water flowing in a stream or through an aquifer past a specific point in a given period.
Discharge area		An area in which groundwater is discharged to the land surface, surface water, or atmosphere (WRC, 1980). reverse process of sorption. See also sorption.
Discretization		The process of subdividing the continuous model and/or time domain into discrete segments or cells. Algebraic equations which approximate the governing flow and/or transport equations are written for each segment of cell.
Discretization, spatial		The process of transferring a continuous spatial model to discrete elements. This requires specification of the size of elements (horizontally and vertically) or more generally the spacing between nodes of those elements.
Discretization, temporal		The process of dividing a continuous period of time into discrete stress periods and time steps (segments) within the numerical model.
Dispersion		Process by which some of the water molecules and solute molecules travel more rapidly than the average linear velocity and some travel more slowly; spreading of the solute in the direction of the groundwater flow (longitudinal) or in the plane perpendicular to groundwater flow (transverse).
Dispersion coefficient		(1) A measure of the spreading of a flowing substance due to the nature of the porous medium, with its interconnected channels distributed at random in all directions (ANS, 1980).

Entry	Acronym	Primary Definition
Dispersion, longitudinal		Process whereby some of the water molecules and solute molecules travel more rapidly than the average linear velocity and some travel more slowly; spreading of the solute in the direction of the bulk flow (after Freeze and Cherry, 1979).
Dispersion, numerical		Artificial dispersion related to improper discretization of the model domain. Characterized by the relationship between the advective time step length and node spacing (see Courant condition and Peclet number).
Dispersion, transverse		Spreading of the solute in directions perpendicular to the bulk flow (after Freeze and Cherry, 1979). Includes components of transverse-horizontal and transverse-vertical dispersion.
Dispersivity		A geometric property of a porous medium which determines the dispersion characteristics of the medium by relating the components of pore velocity to the dispersion coefficient (ANS, 1980).
Disposal well		(1) See injection well.
Distribution coefficient		The quantity of the solute, chemical or radionuclide sorbed by the solid per unit weight of solid divided by the quantity dissolved in the water per unit volume of water (ANS, 1980).
Downgradient		The direction that ground water flows; similar in concept to downstream for surface water, such as a river.
Drainage		A technique to improve the productivity of some agricultural land by removing excess water from the soil; surface drainage is accomplished with open ditches; subsurface drainage uses porous conduits (drain tile) buried beneath the soil surface.
Drainage well		A well installed to drain surface water, storm water, or treated waste water into underground strata (after ASCE, 1985). (2) A water well constructed to remove subsurface water or to reduce a hydrogeologic unit's potentiometric surface (after ASCE, 1985).

Entry	Acronym	Primary Definition
Drawdown		The vertical distance the water elevation is lowered or the reduction of the pressure head due to the removal of water (after ASCE, 1985).
Dupuit Assumptions		The following assumptions for flow in an unconfined aquifer: (a) hydraulic gradient is equal to the slope of the water table, (b) streamlines are horizontal, and (c) equipotential lines are vertical.
E		
Effective hydraulic conductivity	k_{eff}	See hydraulic conductivity, effective.
Effluent stream		See gaining stream.
Eh	Eh	Redox potential. Eh is the numerical measure of the intensity of oxidizing or reducing conditions. A positive potential indicates oxidizing conditions and a negative potential indicates reducing conditions.
Electrical conductivity	EC	1 EC = 1 micro-Siemens per centimetre, measured at 25 °C. It is used as a measure of water salinity.
Element		Also called cell, a distinct two-dimensional or three-dimensional model unit representing a discrete portion of a physical system with uniform properties assigned to it.
Elevation head		That part of hydraulic head which is attributable to the elevation of a measuring point above a given datum (e.g. mean sea level).
Equipotential line		Line (or surface) along which the potential is constant (WMO, 1974).

Entry	Acronym	Primary Definition
Equipotential surface		A surface in a three-dimensional groundwater flow field such that the total hydraulic head is the same everywhere on the surface.
Evaporation		The process by which water or other liquid becomes a gas (water vapor or ammonia vapor). Water from land areas, bodies of water, and all other moist surfaces is absorbed into the atmosphere as a vapor.
Evapotranspiration		The combined loss of water from a given area by evaporation from the land and transpiration from plants (after SSSA, 1975).
Expected Case (Model)		In these guidelines, the term expected case (EC) is used to refer to a working hypothesis or model that in essence reflects the most likely field conditions.
Exchange capacity		The amount of exchangeable ions measured in moles of ion change per kilogram of solid material at a given pH (after ANS, 1980).
F		
Falling head test		An aquifer response test in which a known volume of water is added to a well or is displaced upwards by the insertion of a solid slug. The dynamic water level is monitored as it falls back to the static water level. This decline in head over time is recorded and analyzed to determine the local hydraulic properties of the aquifer.
Fickian diffusion		Spreading of solutes from regions of highest to regions of lower concentrations caused by the concentration gradient. In slow moving groundwater, this is the dominant mixing process (after Freeze and Cherry, 1979).
Fidelity		The degree to which a model application resembles, or is designed to resemble, the physical hydrogeological system (Ritchey and Rumbaugh, 1996). The ASTM guides apply a hierarchical classification of three main fidelities in order of increasing fidelity: Screening, Engineering Calculation, and Aquifer Simulator. Higher fidelity models have a capability to provide for more complex simulations of hydrogeological processes and/or address resource management issues more comprehensively.

Entry	Acronym	Primary Definition
Fidelity, Screening Mode		With limited data availability and status of hydrogeological understanding, and possibly limited budgets, a Screening model could be suitable for preliminary quantitative assessment (rough calculations), or to guide a field programme.
Fidelity, Engineering Calculation or Impact Assessment Model		More detailed assessments are possible with an Engineering Calculation approach, which usually requires more data, better understanding, and greater resources for the study.
Fidelity, Aquifer Simulator		An Aquifer Simulator is a high complexity representation of the groundwater system, suitable for predicting the response of a system to arbitrary changes in hydrogeological conditions.
Field characterization		A review of historical, on-site and off-site, as well as surface and sub-surface data and the collection of new data to meet project objectives; a degree of field characterization is a prerequisite to the development of a conceptual model.
Finite Difference Method	FD	A discretization technique for solving a partial differential equation (PDE) by (1) replacing the continuous domain of interest with a finite number of regular-spaced mesh-points or grid-points (i.e. nodes) representing volume-averaged subdomain properties; and (2) by approximating the derivatives of the PDE for each of these points using finite differences. The resulting set of linear or nonlinear algebraic equations is solved using direct of indirect (iterative) matrix solving techniques.
Finite Element Method	FE	Similar to finite difference method with the exception that (1) the mesh may consist of regular or irregular-spaced grid points which may have irregular shapes (but typically triangular); and (2) the PDE is approximated using the method of weighted residuals to obtain a set of algebraic equations. These algebraic equations are solved using direct or iterative matrix solving techniques.
Field Capacity		See specific retention.
Flow line		The general path that a particle of water follows under laminar flow conditions (after ASTM, 1980).
Flow net		A graphical representation of flow lines and equipotential lines for two-dimensional, steady-state groundwater flow (after ASTM, 1980).

Entry	Acronym	Primary Definition
Flow path		The subsurface course a water molecule or solute would follow in a given groundwater velocity field.
Flow, steady		A characteristic of a flow system where the magnitude and direction of specific discharge are constant in time at any point See also flow, unsteady.
Flow, uniform		A characteristic of a flow system where specific discharge has the same magnitude and direction at any point.
Flow, unsteady		A characteristic of a flow system where the magnitude and/or direction of the specific discharge changes with time.
Flow velocity		See specific discharge.
Fluid potential		The mechanical energy per unit mass of a fluid at any given point in space and time with regard to an arbitrary state and datum (Lohman and others, 1972).
Flux		The volume of water crossing a unit cross-sectional surface area per unit time.
Formation		A group of similar consolidation (that is, relatively solid) rocks of unconsolidated (that is, relatively loose) minerals.
Formation fluid		"Fluid" present in a "formation" under natural conditions as opposed to introduced fluids, such as drilling mud (40 CFR 146.3).
Fractured rock aquifer		These occur in igneous and metamorphosed hard rocks which have been subjected to disturbance, deformation, or weathering, and which allow water to move through joints, bedding planes, and faults. Although fractured rock aquifers are found over a wide area, they contain much less available groundwater than surficial and sedimentary aquifers and, due to the difficulty of obtaining high yields, the quantities of water taken from them are relatively low.
Free water		See gravitational water.
Free water elevation		See water table.
Fresh water		Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids; generally more than 500 mg/L is undesirable for drinking and many industrial uses (USGS, 1984). See also saline water.
G		

Entry	Acronym	Primary Definition
Gaining stream		A stream or reach of a stream whose flow is being increased by inflow of groundwater (ASCE, 1985).
Geohydrologic system		(1) The geohydrologic units within a geologic setting, including any recharge, discharge, interconnections between units, and any natural or human-induced processes or events that could affect groundwater flow within or among those units (10 CFR Part 960.2).
Geohydrologic unit		(2) An aquifer, a confining unit, or a combination of aquifers and confining units comprising a framework for a reasonably distinct geohydrologic system (10 CFR Part 960.2).
Geological log		A detailed description of all underground features discovered during the drilling of a well (depth, thickness and type of formations).
Geophysical log		A record of the structure and composition of the earth encountered when drilling a well or similar type of test hole or boring.
Ghyben-Herzbeg Principle		An equation that relates the depth of a saltwater interface in a coastal aquifer to the height of the freshwater table above sea level.
Graphical User Interface	GUI	A software package that facilitates the data input, flow simulation, and results output of groundwater modelling codes.
Grab sample		A single sample collected at a particular time and place which represents the composition of the water only at that time and place.
Gravitational head		The component of total hydraulic head related to the position of a given mass of water relative to an arbitrary datum (Wilson, 1980).
Gravitational water		Water which moves into, through, or out of the soil or rock mass under the influence of gravity (SSSA, 1975).
Grid		See Model grid. Also called Mesh.

Entry	Acronym	Primary Definition
Groundwater		(1) That part of the subsurface water that is in the saturated zone. (2) Loosely, all subsurface water as distinct from surface water (ASCE, 1985).(3) All water which occurs below the land surface. It includes both water within the unsaturated and saturated zones (NRC, 1985). (4) Means water below the land surface in a zone of saturation. For purpose of this appendix, groundwater is the water contained within an aquifer (10 CFR Part 40 Appendix A). (5) All water which occurs below the land surface (10 CFR Part 60.2). (6) All subsurface water as distinct from surface water (10 CFR Part 960). (7) Subsurface water that fills available openings in rock or soil materials to the extent that they are considered water-saturated (30 CFR Part 710.5 and 710.5). (8) Water below the land surface in a zone of saturation (40 CFR 270.2; 40 CFR 146.3; 40 CFR 144.3). (9) Water in a saturated zone or stratum beneath the surface of land or water (40 CFR 300.6; 40 CFR 257.3-4).
Groundwater barrier		Rock or artificial material which has a relatively low permeability and which occurs below the land surface where it impedes the movement of ground water and consequently causes a pronounced difference in the potentiometric surface on opposite sides of it (after ASCE, 1985).
Groundwater basin		A general term used to define a groundwater flow system that has defined boundaries and may include permeable materials that are capable of storing or furnishing a significant water supply, the basin includes both the surface area and the permeable materials beneath it (after ASCE, 1985).
Groundwater, confined		Groundwater under pressure significantly greater than atmospheric and whose upper limit is the bottom of a confining unit (after Lohman and others, 1972). See also confined, confining unit, and confined aquifer.
Groundwater discharge		(1) Flow of water from the zone of saturation; (2) The water released from the zone of saturation; (3) The quantity of water released (ASCE, 1985).
Groundwater divide		A ridge in the water table or other potentiometric surface from which groundwater moves away in both directions normal to the ridge line (WRC, 1980).

Entry	Acronym	Primary Definition
Groundwater flow		The movement of water in the zone of saturation.
Groundwater flow model		An application of a mathematical model to represent a regional or site-specific groundwater flow system.
Groundwater flow system		A water-saturated aggregate of aquifers and confining units in which water enters and moves and which is bounded by a basal confining unit (that does not allow any vertical water movement) and by zones of interaction with the earth's surface and with surface water systems. A groundwater flow system has two basic hydraulic functions: it is a reservoir for water storage, and it serves as a conduit transmitting water from recharge to discharge areas. May transport dissolved chemical constituents and heat.
Groundwater flux		(1) See specific discharge. (2) The rate of groundwater flow per unit area of porous or fractured media measured perpendicular to the direction of flow (10 CFR Part 960.2).
Groundwater-dependent ecosystems	GDE	For the purposes of defining ecosystem dependence, groundwater may be defined as that water in the system that would be unavailable to plants and animals were it to be extracted by pumping (Hatton and Evans, 1998).
Groundwater modelling code		A computer code used in groundwater modelling to represent a non-unique, simplified mathematical description of the physical framework, geometry, active processes, and boundary conditions present in a reference groundwater system.
Groundwater mound		A raised area in a water table or other potentiometric surface created by groundwater recharge.
Groundwater, perched		(1) See perched groundwater. (2) Unconfined groundwater separated from an underlying body of ground water by an unsaturated zone. Its water table is a perched water table. Perched groundwater is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure (10 CFR Part 960.2).

Entry	Acronym	Primary Definition
Groundwater recharge		The process of water addition to the saturated zone or the volume of water added by this process (ANS, 1980).
Groundwater system		A groundwater reservoir and its contained water. Also, the collective hydrodynamic and geochemical processes at work in the reservoir (USGS, 1984).
Groundwater travel time		The time required for a unit volume of groundwater to travel between two locations. The travel time is the length of the flow path divided by the velocity, where velocity is the average groundwater flux passing through the cross-sectional area of the geologic medium through which flow occurs, perpendicular to the flow direction, divided by the effective porosity along the flow path. If discrete segments of the flow path have different hydrologic properties the total travel time will be the sum of the travel times for each discrete segment (10 CFR Part 960.2).
Groundwater, unconfined		Water in an aquifer that has a water table (Lohman and others, 1972).
Groundwater under the direct influence (UDI) of surface water		Any water beneath the surface of the ground with: 1) significant occurrence of Insects or other microorganisms, algae, or large-diameter pathogens such as Giardia lamblia or, 2) significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH which closely correlate to climatological or surface water conditions. Direct influence must be determined for individual sources in accordance with criteria established by the State. The State determination of direct influence may be based on site-specific measurements of water quality and/or documentation of well construction characteristics and geology with field evaluation.
H		
Head, static		The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head (after Lohman and others, 1972).

Entry	Acronym	Primary Definition
Head, total		The total head of a liquid at a given point is the sum of three components: (a) the elevation head, which is equal to the elevation of the point above a datum, (b) the pressure head, which is the height of a column of static water that can be supported by the static pressure at the point, and (c) the velocity head, which is the height to which the kinetic energy of the liquid is capable of lifting the liquid (Lohman and others, 1972).
Heterogeneity		A characteristic of a medium in which material properties vary from point to point (after ANS, 1980).
Heterogeneous		A medium which consists of different (non-uniform) characteristics in different locations.
History matching		See Verification
Homogeneity		A characteristic of a medium in which material properties are identical everywhere (see Lohman and others, 1972).
Homogeneous		A medium with identical (uniform) characteristics regardless of location.
Hydraulic barrier		A general term referring to modifications of a groundwater flow system to restrict or impede movement of contaminants.
Hydraulic conductance		A term which incorporates model geometry and hydraulic conductivity into a single value for simplification purposes. Controls rate of flow to or from a given model cell, river reach, etc.

Entry	Acronym	Primary Definition
Hydraulic conductivity	k	(1) A proportionality constant relating hydraulic gradient to specific discharge which for an isotropic medium and homogeneous fluid, equals the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (after ASCE, 1985). (2) The volume of water that will move through a medium in a unit of time under a unit hydraulic gradient through a unit area measured perpendicular to the direction of flow (10 CFR Part 960.2).
Hydraulic conductivity, effective		The rate of flow of water through a porous medium that contains more than one fluid, such as water and air in the unsaturated zone, and which should be specified in terms of both the fluid type and content and the existing pressure (Lohman and others, 1972).
Hydraulic diffusivity		See diffusivity, hydraulic.
Hydraulic dispersion		See mechanical dispersion.
Hydraulic diffusivity		A property of an aquifer or confining bed defined as the ratio of the transmissivity to the storativity.
Hydraulic gradient		(1) The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head. (2) Slope of the water table or potentiometric surface (ASCE, 1985). (3) A change in the static pressure of groundwater, expressed in terms of the height of water above a datum, per unit of distance in a given direction (10 CFR Part 960.2).

Entry	Acronym	Primary Definition
Hydraulic head		The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground water system. For a well, the hydraulic head is equal to the distance between the water level in the well and the datum plane (ASCE, 1985).
Hydrochemical facies		Distinct zones that have cation and anion concentrations of diagnostic chemical character of water solutions in hydrologic systems which is describable within defined composition categories (after Freeze and Cherry, 1979).
Hydrodynamic dispersion		The spreading (at the macroscopic level) of the solute front during transport resulting from both mechanical dispersion and molecular diffusion (Bear, 1979).
Hydrogeologic unit		Hydrogeologic unit (1) Any soil or rock unit or zone which by virtue of its hydraulic properties has a distinct influence on the storage or movement of groundwater (after ANS, 1980). (2) Means any soil or rock unit or zone which by virtue of its porosity or permeability, or lack thereof, has a distinct influence on the storage or movement of groundwater (10 CFR Part 61.2).
Hydrogeologic conditions		Conditions stemming from the interaction of ground water and the surrounding soil and rock.
Hydrogeologic cycle		The natural process recycling water from the atmosphere down to (and through) the earth and back to the atmosphere again.
Hydrogeologist		A person who studies and works with groundwater.
Hydrogeology		The geology of ground water, with particular emphasis on the chemistry and movement of water.
Hydrograph		A graph relating stage, flow, velocity, or other characteristics of water with respect to time (after ASCE, 1985).
Hydrologic conditions		A set of groundwater inflows, outflows, boundary conditions, and hydraulic properties that causes potentiometric heads to adopt a distinct pattern.
Hydrologic cycle		Movement or exchange of water between the atmosphere and the earth.

Entry	Acronym	Primary Definition
Hydrologic equation		An expression of the law of mass conservation for purposes of water budgets. It may be stated as inflow equals outflow plus or minus changes in storage.
Hydrologic properties		Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity, effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities (10 CFR Part 960.2).
Hydrologic unit		Geologic strata that can be distinguished on the basis of capacity to yield and transmit fluids. Aquifers and confining units are examples. Boundaries of a hydrologic unit may not necessarily correspond to those of lithostratigraphic units.
Hydrology		The study of the occurrence, distribution and circulation of the natural waters of the earth.
Hydrostratigraphic unit		See hydrogeologic unit.
I		I
Immiscible		(1) Two or more liquids that are not readily soluble (AGI, 1980). (2) The chemical property of two or more phases that, at mutual equilibrium, cannot dissolve completely in one another, e.g. oil and water (AGI, 1980).
Impermeable		A characteristic of some geologic material that limits its ability to transmit significant quantities of water under the head differences ordinarily found in the subsurface (after ASCE, 1985).
Impermeable layers		Layers of rock which do not allow water to pass through them.
Initial conditions		The specified values for the dependent variable (hydraulic head or solute concentration) at the beginning of thee model simulation.
Infiltration		The downward entry of water into the soil or rock (SSSA, 1975).
Infiltration capacity		The maximum rate at which a soil or rock is capable of absorbing water or limiting infiltration (after ASCE, 1985).

Entry	Acronym	Primary Definition
Infiltration rate		(1) The rate at which a soil or rock under specified conditions absorbs falling rain, melting snow, or surface water expressed in depth of water per unit time (ASCE, 1985). (2) A characteristic describing the maximum rate at which water can enter the soil or rock, under specified conditions, including the presence of an excess of water. It has the dimensions of velocity (SSSA, 1975).
Influent stream		See losing stream.
Injection well		(1) Well used for injecting fluids into the subsurface. (2) A well into which fluids are being injected (40 CFR Parts 144.3; 146.3; and 270.2).
Injection zone		A geological "formation," group of formations, or Dart of a formation receiving fluids through a well (40 CFR Part 146.3).
In situ		In place, the original location, in the natural environment.
In situ density		The density of water measured at its actual depth (AGI, 1980). See potential density.
Interface		The contact zone between two materials of different chemical or physical composition (after USGS, 1984).
Interflow		The lateral movement of water in the unsaturated zone during and immediately after a precipitation event. The water moving as interflow discharges directly into a stream or lake.
Interstice		(1) An opening in a rock or soil that is not occupied by solid matter (AGI, 1980). (2) An opening or space which may be occupied by air, water, or other gaseous or liquid material (ASTM, 1980).
Intrinsic permeability		A term describing the relative ease with which a porous medium can transmit a liquid under a hydraulic gradient or potential gradient. It is distinguishable from hydraulic conductivity in that it is a property of the porous medium alone and is independent of the nature of the liquid or the potential field.
Inverse method		A method of calibrating a groundwater flow model using a computer code to systematically vary inputs or input parameters to minimize residuals or residual statistics.

Entry	Acronym	Primary Definition
Inverse-distance weighed	IDW	One of the most common interpolation schemes for estimating spatial distributions of data. Inverse distance weighted methods are based on the assumption that the interpolating surface should be influenced most strongly by the nearby points and less by the more distant points. The interpolating surface is a weighted average of the scatter points and the weight assigned to each scatter point diminishes as the distance from the interpolation point to the scatter point increases.
Irrigation return flow		The part of artificially applied water that is not consumed by evapotranspiration and that migrates to an aquifer or surface water body (USGS, 1984).
Isotropic mass		A mass having the same property or properties in all directions (AGI, 1980).
Isotropy		The condition in which the property or properties of interest are the same in all directions.
J		
K		
Karst		The type of geologic terrain underlain by carbonate rocks where significant solution of the rock has occurred due to the flowing groundwater. Karst topography is frequently characterized by sinkholes, caves, and underground drainage.
Kriging		A geostatistical interpolation procedure for estimating spatial distributions of model inputs from scattered observations.
L		
Laminar flow		Flow in which the head loss is proportional to the first power of the velocity (ASTM, 1980).
Layer		

Entry	Acronym	Primary Definition
Leachate		(1) Materials removed by the process of leaching. (2) A liquid that has percolated through soil, rock or waste and has extracted dissolved or suspended materials (30 CFR Part 710.5).
Leaching		(1) The removal of materials in solution from soil, rock, or waste (after SSSA, 1975). (2) Separation or dissolving out of soluble constituents from a porous medium by percolation of water (McGraw-Hill, 1974).
Leakage		(1) The flow of water from one hydrogeologic unit to another. The leakage may be natural, as through semi-impervious confining layer, or human-made, as through an uncased well (APHA, 1981). (2) The natural loss of water from artificial structures as a result of hydrostatic pressure.
Leakance		(1) The ratio K'/b', in which K' and b' are the vertical hydraulic conductivity and the thickness, respectively, of the confining beds (Lohman and others, 1972). (2) The rate of flow across a unit (horizontal) area of a semipervious layer into (or out of) an aquifer under one unit of head difference across this layer (Bear, 1979). Synonymous with coefficient of leakage.
Leaky aquifer		Aquifers, whether artesian or water-table, that lose or gain water through adjacent less permeable layers (after Hantush, 1964).
Leaky confining layer		A low-permeability layer that can transmit water at sufficient rates to furnish some recharge to a well pumping from an underlying aquifer. Also know as an aquitard.
Lineament		A regional topographic feature of regional extent that is believed to reflect crustal structure.
Line of seepage		See seepage line.
Local groundwater system		Aquifers which respond rapidly to recharge due to a shallow watertable and/or close proximity of the recharge to discharge sites. These types of flow systems occur almost exclusively in unconfined aquifers.
Losing stream		A stream or reach of a stream in which water flows from the stream bed into the ground (ASCE, 1985). Synonymous with influent stream.

Entry	Acronym	Primary Definition
Lower bound (model)		The most favorable conditions compatible with the available data about the system being modeled.
Lysimeter		A device for measuring percolation and leaching losses from a column of soil under controlled conditions (SSSA, 1975).
M		
Manning's equation		An equation that can be used to compute the average velocity of flow in an open channel.
Matric potential		The energy required to extract water from a porous medium to overcome the capillary and adsorptive forces (after Wilson, 1980).
Matrix		The solid framework of a porous system (Wilson, 1980).
Mechanical dispersion		The process whereby solutes are mechanically mixed during advective transport caused by the velocity variations at the microscopic level. Synonymous with hydraulic dispersion.
Mechanical dispersion, coefficient		The component of mass transport flux of solutes caused by velocity variations at the microscopic level (after Bear, 1979). Synonymous with convective diffusion.
Mine, open pit		A mineral extraction project where the ore is exposed by removal of surface overburden soil and/or rock, then extracted and processed above ground.
Mine, underground		A mineral extraction project where ore is extracted from the subsurface via underground mine workings (adits, shafts, drifts, stopes, etc.).
Mining		The process of extracting and processing ore from the earth and the management of associated waste products.
Miscible		(1) Said of two or more liquids that are mutually soluble (i.e. they will dissolve in each other) (McGraw-Hill, 1974).
Mixed boundary		A linear combination of head and flux at a boundary. An example of a mixed boundary is leakage between a river and an underlying aquifer.

Entry	Acronym	Primary Definition
Model		(1) A conceptual, mathematical, or physical system obeying certain specified conditions, whose behavior is used to understand the physical system to which it is analogous in some way (after McGraw Hill, 1974).
Model, analytical		See Analytical model
Model, baseline		See Baseline model
Model, conceptual		A simplified and idealized representation (usually graphical) of the physical hydrogeologic setting and our hydrogeological understanding of the essential flow processes of the system. This includes, the identification and description of the geologic and hydrologic framework, media type, hydraulic properties, sources and sinks, and important aquifer flow ad surface-groundwater interaction processes.
Model, groundwater		An application of a mathematical model to represent a site-specific groundwater flow system. A groundwater model provides a scientific means to synthesize the available data into a numerical characterization of a groundwater system. The model represents the groundwater system to an adequate level of detail, and provides a predictive tool to quantify the effects on the system of specified hydrological stresses.
Model, mathematical		A mathematical model is a set of equations, which subject to certain assumptions, quantifies the physical processes active in the aquifer. While the model itself obviously lacks the detailed reality of the groundwater system, the behaviour of a valid model approximates that of the aquifer.
Model, numerical		See Numerical model
Model, predictive		See Predictive model
Model grid		In numerical modelling, a system of connected nodes superimposed over the problem domain to spatially discretize the domain into cells (finite difference method) or elements (finite element method). Also called Mesh.

Entry	Acronym	Primary Definition
Model input		The constitutive coefficients, system parameters, forcing terms, auxiliary conditions, and program control parameters required to apply a computer code to a particular problem.
Modelling		Use of mathematical equations to simulate and predict real events and processes.
Model verification		In model application, (1) the procedure of determining if a (site-specific) model's accuracy and predictive capability lie within acceptable limits of error by tests independent of the calibration data; (2) using the set of parameter values and boundary conditions from a calibrated model to acceptably approximate a second set of field data measured under similar hydrologic conditions. Also referred to as History Matching.
Moisture content		Moisture content - The ratio, expressed as a percentage, of either (a) the weight of water to the weight of solid particles expressed as moisture weight percentage or (b) the volume of water to the volume of solid particles expressed as moisture volume percentage in a given volume of porous medium (ASTM, 1980). See water content.
Moisture equivalent		Moisture equivalent - The percentage of water retained in a soil sample 1 cm thick after it has been saturated and subjected to a centrifugal force 1000 times gravity for 30 minutes (SSSA, 1975). Centrifuge moisture equivalent is the water content of a soil after it has been saturated with water and then subjected for 1 hour to a force equal to 1000 times that of gravity (ASTM, 1980).
Moisture retention		Moisture tension - The equivalent negative pressure of water in an unsaturated porous medium equal to the pressure that must be applied to the medium to bring the water to hydraulic equilibrium through a porous permeable material with a pool of water of the same composition (after SSSA, 1975).
Moisture volume percentage		Moisture volume percentage - The ratio of the volume of water in a soil to the total bulk volume of the soil (SSSA, 1975).

Entry	Acronym	Primary Definition
Moisture weight percentage		Moisture weight percentage - The moisture content expressed as a percentage of the oven-dry weight of a soil (SSSA, 1975).
Molecular diffusion		Molecular diffusion (diffusion) - The process whereby solutes are transported at the microscopic level due to variations in the solute concentrations within the fluid phases.
Molecular diffusion, coefficient of		Molecular diffusion, coefficient of, - The component of mass transport flux of solutes (at the microscopic level) due to variations in solute concentrations within the fluid phases (after Bear, 1979). Synonymous with diffusion coefficient.
Monte Carlo (Analysis/Simulation)		A set of model simulations for alternative model realizations, on the assumption that aspects of the model are stochastic. A realization is one of many possible valid descriptions of a model in terms of its aquifer parameters, boundary conditions, or stresses.
N		
Neumann Condition		Also called a constant flux boundary. The boundary condition for a groundwater flow model where a flux across the boundary of the flow region is known and specified, and the mode computes the associated aquifer head.
Node		Also Nodal point. In a numerical model, a location in the discretized model domain where a dependent variable is computed.
No-Flow boundary		A specified-head boundary where the assigned flux is equal to zero.
Non-uniqueness		The principle that many different possible sets of model inputs can produce nearly identical computed aquifer head distributions for any given model.
Nonpoint source		(1) Any source, other than a point source, which discharges pollutants into air or water (APHA, 1981). (2) Source originating over broad areas, such as areas of fertilizer and pesticide application and leaking sewer systems, rather than from discrete points (after USGS, 1988).

Entry	Acronym	Primary Definition
Numerical methods		In subsurface fluid flow modelling, a set of procedures used to solve the groundwater flow equations in which the applicable partial differential equations are replaced by a set of algebraic equations written in terms of discrete values of state variables (e.g. hydraulic head) at discrete points in space and time. The most commonly used numerical methods in groundwater models are the finite-difference method, the finite element method, the boundary element method, and the analytic element method.
Numerical model		A model of groundwater flow in which the aquifer is described by numerical equations, with specified values for boundary conditions , that are usually solved on a digital computer. In this approach, the continuous differential terms in the governing hydraulic flow equation are replaced by finite quantities. The computational power of the computer is used to solve the resulting algebraic equations with matrix arithmetic. In this way, problems with complex geometry, dynamic response effects and spatial and temporal variability may be solved accurately. This approach must be used in cases where the essential aquifer features form a complex system, and where surface-groundwater interaction is an important component (i.e. high complexity models).
Numerical disperison		Artificial dispersion related to improper discretization of the model domain. Characterized by the relationship between the advective time step length and node spacing (see Courant condition and Peclet number).
Numerical oscillation		Numerical instabilities in the transport calculation of diffusion/dispersion terms (see Von Neumann criteria).
Numerical solution		An approximate solution of a governing (partial) differential equation derived by replacing the continuous governing equation with a set of equations in discrete points of the model's time and space domains.
O		

Entry	Acronym	Primary Definition
Observation well		A non-pumping well used to observe the elevation of the water table or the potentiometric surface. An observation well is generally of larger diameter than a piezometer and typically is screened or slotted throughout the thickness of the aquifer.
Output		All information that is produced by the computer code.
Over-calibration		Achieving artificially low residuals by inappropriately adjusting model input parameters without field data to support the adjusted model parameter values.
P		
Packer test		An aquifer test performed in an open borehole; the segment of the borehole to be tested is sealed off from the rest of the borehole by inflating seals, called packers, both above and below the segment.
Parameter		Any of a set of physical properties which determine the characteristics or behaviour of a system.
Parameter Identification Model (inverse model)		A computer code for determination of selected unknown parameters and stresses in a groundwater system, given that the response of the system to all stresses is known and that information is available regarding certain parameters and stresses.
Partitioning function		A mathematical relation describing the distribution of a reactive solute between solution and other phases.
Parsimony		The parsimony principle implies that a conceptual model has been simplified as much as possible, yet it retains enough complexity so that it adequately represents the physical system and its behaviour.
Partial differential equation	PDE	In numerical modelling of groundwater flow and solute transport, an equation containing partial differential terms that completely describes the physical processes of the system.
Particle tracking		This technique typically uses the output from hydrodynamic and/or advection-diffusion models to predict particle movements. The flow regime is seeded with particles that are tracked as they move through the system.
Particulate transport		Particulate transport - The movement of particles in subsurface water.

Entry	Acronym	Primary Definition
Partitioning function		A mathematical relation describing the distribution of a reactive solute between solution and other phases.
Pathline analysis		See particle tracking
Pathway, preferential		A path of significantly lower resistance to flow (higher transmissivity) compared to the surrounding hydrogeologic formation(s).
Peclet number		In numerical modelling, a relationship between the advective and diffusive components of solute transport expressed as the ratio of the product of the average interstitial velocity, times the characteristic length, divided by the coefficient of molecular diffusion; small values indicate diffusion dominance, large values indicate advection dominance.
Percent saturation		The ratio, expressed as a percentage, of (a) the volume of water to (b) the total volume of intergranular space (voids) in a given porous medium (ASTM, 1980). Synonymous with degree of saturation.
Perched groundwater		(1) Groundwater separated from an underlying body of groundwater by an unsaturated zone (ASCE, 1985). (2) Unconfined groundwater separated from an underlying body of ground water by an unsaturated zone. Its water table is a perched water table. Perched groundwater is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure (10 CFR Part 960.2).
Pellicular water		(1) The film of water left around each grain or fracture surface of water-bearing material after gravity drainage (after APHA, 1981). (2) Water of adhesion; (after APHA, 1981). (3) Water that can be extracted by root absorption and evaporation but cannot be moved by gravity or by the unbalanced film forces resulting from localized evaporation and transpiration (after APHA, 1981).
Percolation		(1) The downward movement of water through the unsaturated zone. (2) The downward flow of water in saturated or nearly saturated porous medium at hydraulic gradients of the order of 1.0 or less (after SSSA, 1975).
Permeability		The property of a porous medium to transmit fluids under a hydraulic gradient.

Entry	Acronym	Primary Definition
Permeability coefficient		The rate of flow of water through a unit cross-sectional area under a unit hydraulic gradient at the prevailing temperature (field permeability coefficient) or adjusted to a temperature of 150C (60-F) (ASCE, 1985).
Permeability, effective		The observed permeability of a porous medium to one fluid phase under conditions of physical interaction between this phase and other fluid phases present (AGI, 1980).
Permeability, intrinsic		(1) A measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient and is a property of the medium alone (after Lohman and others, 1972).
Permeability, relative		(1) The ratio of the effective permeability for a given flow phase to the intrinsic permeability of the porous medium (WMO, 1974).
Permeability, specific		The permeability measured when the rock contains only one fluid (Thrush, 1968).
Permeable strata		Layers of rock or soil through which water can pass.
Perturbation		See Stress (hydrologic)
Phreatic line		See seepage line.
Phreatic surface		See water table.
Piezometer		A devise used to measure groundwater pressure head at a point in the subsurface.
Piezometric surface		See potentiometric surface.
Pit, Open		See Mine, open pit

Entry	Acronym	Primary Definition
Point source		A stationery location or fixed facility from which pollutants are discharged or emitted. Also, any single identifiable source of pollution, e.g., a pipe, ditch, ship, ore pit, factory smokestack.
Pollution		(1) Specific impairment of water quality by agricultural, domestic, or industrial wastes (including thermal and atomic wastes), to a degree that has an adverse effect upon any beneficial use of water.
Pore		See interstice.
Pore space		The total space not occupied by solid soil or rock particles (SSSA, 1975).
Pore velocity		See velocity, average interstitial.
Porosity		(1) The ratio, usually expressed as a percentage, of the total volume of voids of a given porous medium to the total volume of the porous medium (after ASTM, 1980). (2) The volume percentage of the total bulk not occupied by solid particles (SSSA, 1975).
Porosity, effective		(1) The ratio of the volume of the voids of a soil or rock mass that can be drained by gravity to the total volume of the mass (ASTM, 1980). (2) The amount of interconnected pore space and fracture openings available for the transmission of fluids, expressed as the ratio of the volume of interconnected pores and openings to the volume of rock (10 CFR Part 960.2). (3) The amount of interconnected pore space and fracture openings available for transport of solutes, expressed as the ratio of the volume of interconnected pores and openings to the total volume of aquifer material (soils or rock).

Entry	Acronym	Primary Definition
Porosity, primary		The porosity that represents the original pore openings when a rock or sediment formed.
Porosity, secondary		The porosity that has been caused by fractures or weathering in a rock or sediment after it has been formed.
Post-audit		Comparison of model predictions with what actually happened.
Post-processing		Using computer programs to analyze, display, and store results of model simulations.
Potable water		Water that is suitable for human consumption.
Potential		Any of several different scalar quantities, each of which involves energy as a function of position or of condition; e.g. the fluid potential of groundwater (AGI, 1980).
Potential density		(1) The density of a unit of water after it is raised by an adiabatic process to the surface, i.e., determined from in-situ salinity and potential temperature (AGI, 1980).
Potential drop		The difference in total head between two equipotential lines (ASTM, 1980).
Potentiometric surface		An imaginary surface representing the static head of groundwater and defined by the level to which water will rise in a tightly cased well (after Lohman and others, 1972).
Precision		The degree to which repeated simulations or trials produce the same results.
Predictive model		A model (usually based on a preceding baseline model) which seeks to replicate the future conditions as a result of changes in the hydrogeological system.

Entry	Acronym	Primary Definition
Preprocessing		Using computer programs to assist in preparing data sets for use with generic simulation codes; may include grid generaton, parameter allocation, control parameter selection, and data file formatting.
Pressure head		Hydrostatic pressure expressed as the height of a column of water that the pressure can support at the point of measurement. See also head, static, and pressure, hydrostatic.
Pressure, hydrostatic		The pressure exerted by the weight of water at any given point in a body of water at rest (after AGI, 1972).
Probabilistic (analysis)		Parameter uncertainty is described using frequency distributions and statistics.
Probability distribution function	PDF	A graph or formula that expresses the probability that an uncertain parameter will be less than or equal to a particular value.
Proponent		Applicant for an Environmental Assessment Certificate, Mine Permit, or other similar regulatory permission to execute a mine, quarry, or groundwater extraction project.
Pumping test		Also known as an aquifer test. A test made by pumping a well for a period of time at a measured rate and observing the change in hydraulic head in the aquifer. A pumping test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer.
Q		
R		
Range		The spread from minimum to maximum values that an instrument is designed to measure.
Reaction path modelling		A simulation approach to studying the chemical evolution of a (natural) system.
Receiving Waters		All distinct bodies of water that receive runoff or wastewater discharges, such as streams, rivers, ponds, lakes, and estuaries.

Entry	Acronym	Primary Definition
Recharge		The process of addition of water to the saturated zone; also the water added (USGS, 1984).
Recharge area		An area in which water reaches the zone of saturation by surface infiltration (Heath, 1984).
Recharge boundary		An aquifer system boundary that adds water to the aquifer. Streams and lakes are typically recharge boundaries.
Recharge capacity		The ability of the soils and underlying materials to allow precipitation and runoff to infiltrate and reach the zone of saturation (30 CFR Parts 701.5 and 710.5).
Regional groundwater systems		Extensive aquifers which take longer than local systems to respond to increased groundwater recharge because their recharge and discharge sites are separated by large distances (>10 km), and/or they have a deep water table. Unconfined aquifers with deep watertables that are part of regional flow systems may become, in effect, local flow systems if there is sufficient recharge to cause the watertable to rise close to the surface (<5m).
Regolith		The fragmented and unconsolidated rock material that forms the surface of the land and overlies the bedrock.
Regulator		One who enforces government regulation and who assesses applications for the execution of natural resource extraction projects.
Remedial Design		Engineering design of a remediation strategy.
Remediation (environmental)		The removal, reduction, or neutralization of substances, wastes or hazardous material from a site so as to prevent or minimize any adverse effects on the environment now or in the future.
Representative elementary volume	REV	The smallest volume of an aquifer taken to have hydraulic properties and heterogeneity representative of the entire aquifer.

Entry	Acronym	Primary Definition
Representative sample		A portion of material or water that is as nearly identical in content and consistency as possible to that in the larger body of material or water being sampled.
Residual		The difference between the computed and observed value of a variable at a specific time and location.
Response Test		An aquifer test in which a hydrological stress is applied and the reaction of the groundwater system is monitored. The results are typically analyzed to provide estimates of aquifer properties.
Retardation factor		The ratio of the average linear velocity of groundwater to the velocity of the retarded constituent at C/Co=0.5 (after Freeze and Cherry, 1979).
Reviewer, (Model)		One who reviews a groundwater model in the context of a regulatory assessment of the project.
Rising head test		An aquifer response test in which the water level in a well is rapidly lowered below the static water level. The dynamic water level is monitored as it rises back to the static water level. This increase in head over time is recorded and analyzed to determine the local hydraulic properties of the aquifer.
Risk		The potential for realization of unwanted adverse consequences or events.
Risk Assessment		A qualitative or quantitative evaluation of the environmental and/or health risk resulting from exposure to a chemical or physical agent (pollutant); combines exposure assessment results with toxicity assessment results to estimate risk.
Risk Characterization		Final component of risk assessment that involves integration of the data and analysis involved in hazard evaluation, dose-response evaluation, and human exposure evaluation to determine the likelihood that humans will experience any of the various forms of toxicity associated with a substance.
Risk Estimate		A description of the probability that organisms exposed to a specified dose of chemical will develop an adverse response (e.g., cancer).

Entry	Acronym	Primary Definition
Risk Management		Decisions about whether an assessed risk is sufficiently high to present a public health concern and about the appropriate means for control of a risk judged to be significant.
Rock, igneous		A rock formed by the cooling and crystallization of a molten rock mass called magma.
Rock, metamorphic		A rock formed by the application of heat and pressure to pre-existing rock.
Rock, sedimentary		A layered rock formed from the consolidation of sediment. Includes clastic rocks (such as sandstone), rocks formed by chemical precipitation in water (such as limestone), or rocks formed from organic material (such as coal).
Rocks, volcanic		An igneous rock formed when molten rock called lava cools on the earth's surface.
Root Mean Square Error	RMSE	A calibration metric frequently used to quantify the differences between values predicted by a model and the values actually observed (typically head measurements). RMSE is a good measure of accuracy.
Root Mean Square Error, Normalized	NRMSE	The normalized root mean square error is the RMSE divided by the range of observed values. The value is often expressed as a percentage, where lower values indicate less residual variance.
Run-off		That part of precipitation, snow melt, or irrigation water that runs off the land into streams or other surface water. It can carry pollutants from the air and land into the receiving waters.
S		
Safe Yield		The annual quantity of water that can be taken from a source of supply over a period of years without depleting the source beyond its ability to be replenished naturally in "wet years".

Entry	Acronym	Primary Definition
Saline Water		Water that generally is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids. Commonly expressed as milligrams per liter (mg/L) of dissolved solids, with 35,000 mg/L defined as equivalent to sea water, slightly saline as 1,000 - 3,000 mg/L, moderately saline as 3,000 - 10,000 mg/L, very saline as 10,000 - 35,000 mg/L, and brine has more than 35,000 mg/L (after USGS, 1984).
Salinity		The concentration of sodium chloride or dissolved salts in water, usually expressed in EC units or milligrams of total dissolved solids per litre (mg/L TDS). The conversion factor of 0.6 mg/L TDS = 1 EC unit is commonly used as an approximation.
Salinisation		The accumulation of salts via the actions of water in the soil to a level that causes degradation of the soil.
Saltwater intrusion		The movement of salt water into fresh water aquifers (ASCE, 1985).
Saturated zone		Saturated zone (1) Those parts of the earth's crust in which all voids are filled with water under pressure greater than atmospheric (Lohman and others, 1972). (2) That part of the earth's crust beneath the regional water table in which all voids, large and small, are filled with water under pressure greater than atmospheric (after NRC, 1985). (3) Means that part of the earth's crust beneath the regional water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric (10 CFR Part 60.2). 22 (4) Means that part of the earth's crust beneath the water table in which all voids, large or small, are ideally filled with water under pressure greater than atmospheric (10 CFR Part 960.2).
Scoping simulation		Predictive model runs carried out without previous calibration of the model, or in the absence of a baseline model
Seasonal		Occurring at or dependent on a particular season (e.g. head measurements in wet or dry seasons, ephemeral streams, etc.)

Entry	Acronym	Primary Definition
Sedimentary aquifers		These occur in consolidated sediments such as porous sandstones and conglomerates, in which water in stored in the intergranular pores, and limestone, in which water is stored in solution cavities and joints. The aquifers are generally located in sedimentary basins that are continuous over large areas and may be tens or hundreds of metres thick. In terms of quantity, they contain the largest groundwater resources.
Seep		(1) An area, generally small, where water percolates slowly to the land surface (see seepage and spring) (AGI, 1980). (2) To move slowly through small openings of a porous material (AGI, 1980).
Seepage		Seepage (1) The fluid discharged at a seep. (2) The amount of fluid discharged at a seep.
Seepage face		A boundary between the saturated flow field and the atmosphere along which groundwater discharges, either by evaporation or movement "downhill" along the land surface or in a well as a thin film in response to the force of gravity (after Franke and others, 1985).
Seepage line		(1) The uppermost level at which flowing water emerges along a seepage face (AGI, 1980). (2) The upper free water surface of the zone of seepage (ASTM, 1980). Synonymous with line of seepage, phreatic line.
Seepage velocity		See specific discharge.
Semi-analytical model		A mathematical model in which complex analytical solutions are evaluated using approximate techniques, resulting in a solution discrete in either the space or time domain.
Semiconfined aquifer		See leaky aquifer.

Entry	Acronym	Primary Definition
Sensitivity		The variation in the value of one of more output variables (such as hydraulic heads) or quantities calculated from the output variables (such as groundwater flow rates) due to changes in the value of one or more inputs to a groundwater flow model (such as hydraulic properties or boundary conditions).
Sensitivity analysis		The measurement of the uncertainty in a calibrated model as a function of uncertainty in estimates of aquifer parameters and boundary conditions.
Sensitivity Type I		An insignificant change in calibration results in an insignificant change in prediction.
Sensitivity Type II		A significant change in calibration results in an insignificant change in prediction.
Sensitivity Type III		A significant change in calibration results in a significant change in prediction. This sensitivity type is of concern for low complexity models that are essentially uncalibrated.
Sensitivity Type IV		An insignificant change in calibration results in a significant change in prediction. As non-uniqueness can allow for several valid calibration schemes, this sensitivity is a cause for concern, even in models calibrated extensively.
Simulation		One complete execution of a groundwater modelling program, including input and output. Simulation is sometimes also used broadly to refer to the process of modelling in general.
Simplicity		The simplicity (or parsimony) principle implies that a conceptual mode has been simplified as much as possible, yet it retains enough complexity so that it adequately represents the physical system and its behaviour.
Sink		A place in the environment where a compound or material collects.

Entry	Acronym	Primary Definition
Site Characterization		(1) A general term applied to the investigation activities at a specific location that examines natural phenomena and human-induced conditions important to the resolution of environmental, safety and water-resource issues. (2) Means the program of exploration and research, both in the laboratory and in the field, undertaken to establish the geologic conditions and the ranges of those parameters of a particular site relevant to the program. Site characterization includes borings, surface excavations, excavation of exploratory shafts, limited subsurface lateral excavations and borings, and in situ testing at depth needed to determine the suitability of the site for a geologic repository but does not include preliminary borings and geophysical testing needed to decide whether site characterization should be undertaken (10 CFR Part 960.2). 23 (3) Activities, whether in the laboratory or the field, undertaken to establish the geologic conditions and the ranges of the parameters of a candidate site relevant to the location of a repository, including borings, surface excavations, excavation of exploratory shafts, limited surface lateral excavations and borings, and in situ testing needed to evaluate the suitability of a candidate site for the location of a repository, but not including preliminary borings and geophysical testing needed to assess whether site characterization should be undertaken (10 CFR Part 960.2).
Slug test		An aquifer response test where a volume of water is added or subtracted from a well and the rise or fall of the water level back to the pre-disturbance level is monitored. The displacement-time data is analyzed to estimate hydraulic properties of the local aquifer.
Soil bulk density		The mass of dry soil per unit bulk soil (SSSA, 1975).
Soil moisture		Subsurface liquid water in the unsaturated zone expressed as a fraction of the total porous medium volume occupied by water. It is less than or equal to the porosity, n (NRC, 1985).
Soil water		See soil moisture.

Entry	Acronym	Primary Definition
Soil-water pressure		The pressure (positive or negative), in relation to the external gas pressure on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water (SSSA, 1975).
Sole Source Aquifer		An aquifer that supplies 50 percent or more of the drinking water of an area.
Solubility		The total amount of solute species that will remain indefinitely in a solution maintained at constant temperature and pressure in contact with the solid crystals from which the solutes were derived.
Solute		The substance present in a solution in the smaller amount. For convenience, water is generally considered the solvent even in concentrated solutions with water molecules in the minority.
Solute transport		The net flux of solute through a hydrogeologic unit controlled by the flow of subsurface water and transport mechanisms.
Solution		A homogeneous mixture of two or more components. In ideal solutions, the movement of molecules in charged species are independent of each other. In aqueous solutions charged species interact even at very low concentrations, decreasing the activity of the solutes.
Sorption		(1) A general term used to encompass the process of absorption and adsorption. (2) All processes which remove solutes from the fluid phase and concentrate them on the solid phase of the medium (after ANSI, 1980).
Source term		The kinds and amounts of radionuclides that make up the source of a potential release of radioactivity (10 CFR Part 960.2).
Specific capacity		The rate of discharge of water from the well divided by the drawdown of the water level within the well (Lohman and others, 1972).

Entry	Acronym	Primary Definition
Specific conductance		A measure of the ability of water to conduct an electrical current expressed in micromhos per centimeter at 25'C (ASCE, 1985).
Specific discharge		The rate of discharge of groundwater per unit area of a porous medium measured at right angle to the direction of flow (Lohman and others, 1972). Synonymous with flow velocity or specific flux.
Specific retention		The ratio of the Volume of water which the porous medium, after being saturated, will retain against the pull of gravity to the volume of the porous medium (Lohman and others, 1972).
Specific storage		The volume of water released from or taken into storage per unit volume of the porous medium per unit change in head (Lohman and others, 1972).
Specific yield		The ratio of the volume of water which the porous medium after being saturated, will yield by gravity to the volume of the porous medium (Lohman and others, 1972).
Spring		A discrete place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water (ASCE, 1985). See also seep.
Static		See head, static.
Static water depth		The vertical distance in feet from the centerline of the pump discharge down to the surface level of the free pool while no water is being drawn from the pool or water table.
Static water level		The elevation or level of the water table in a well when the pump is not operating.
Steady state		A condition where the system properties (e.g. head distribution and flow) are unchanging with time.
Stochastic		Based on the assumption that the variables in a natural process result from probabilistic events.

Entry	Acronym	Primary Definition
Storage coefficient		The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (virtually equal to the specific yield in an unconfined aquifer) (Lohman and others, 1972).
Streamline		A line (commonly transverse to groundwater contours) that represents the flow path for a particle of water.
Storativity		See storage coefficient.
Stress, hydrologic		The addition or abstraction of water from a groundwater system, or an imposed change in flow.
Stress period		A computational time period in a computer model. For a steady-state simulation, there is one stress period. For a transient simulation, there may be many stress periods. A new stress period must be defined in the model set-up whenever transient stresses (e.g. pumping rates, river stages, etc.) are to change in the model.
Sub-artesian		Groundwater that does not rise above the surface of the ground when accessed by a bore and must be pumped to the surface.
Subsurface water		All water that occurs below the land surface.
Subirrigation		(1) Irrigation of plants with water delivered to the roots from underneath (30 CFR Part 710.b). (2) With respect to alluvial valley floors, the supplying of water to plants from underneath or from a semisaturated or saturated subsurface zone where water is available for use by vegetation (30 CFR Part 701.5).
Suction		See moisture tension.
Surface runoff		Precipitation, snow melt, or irrigation in excess of what can infiltrate the soil surface and be stored in small surface depressions; runoff is a major transporter of non-point source pollutants.
Surface water		All water naturally open to the atmosphere (rivers, lakes, reservoirs, streams, impoundments, seas, estuaries, etc.) and all springs, wells, or other collectors which are directly influenced by surface water.

Entry	Acronym	Primary Definition
Surficial (Superficial) Aquifers		They occur in alluvial sediments in river valleys, deltas, basins and coastal plains, in lacustrine (lake) sediments, and in aeolian (wind-formed) deposits. They are essentially unconsolidated clay, silt, sand, gravel, and limestone formations, mainly of Quaternary age (under 1.8 million years). These deposits are easily exploited and are the major sources or freshwater groundwater when associated with larger river systems.
T		
Tailings		Fine to coarse mill waste produced during ore processing.
Tailings Storage Facility	TSF	A reservoir controlled by one or more embankments to store mine tailings and mine process water (supernatant). Tailings are fine rock materials in suspension, which are discharged from an ore concentrator or coal preparation plant. A TSF includes any started dams, seepage collection dams and ponds located beyond the downstream toe of the main embankment(s).
Tensiometer		A device used to measure the moisture tension in the unsaturated zone.
Theis Equation		An equation for the unsteady flow of groundwater in a fully confined aquifer to a pumping well.
Time step		A sub-division of a stress period in a transient simulation, the frequency of which should be determined by examination of the Courant and Von Neumann criteria for solute transport simulations.
Topographic divide		The boundary between adjacent surface water boundaries. It is represented by a topographically high area.
Tortuosity		The actual length of a groundwater flow path, which is sinuous in form, divided by the straight-line distance between the ends of the flow path.

Entry	Acronym	Primary Definition
Total dissolved solids	TDS	(1) The total concentration of dissolved constituents in solution, usually expressed in milligrams per liter. (2) The total concentration of dissolved material in water [as] ordinarily determined from the weight of the dry residue remaining after evaporation of the volatile portion of an aliquot of the water sample (Hem, 1985). (3) The total dissolved (filterable) solids as determined by use of the method specified in 40 CFR Part 136 (40 CFR 144.3; 40 CFR 146.3).
Total hydraulic head		See head, total.
Total soil-water potential		The sum of the energy-related components of a soil-water system; i.e., the sum of the gravitational, matric, and osmotic components (Wilson, 1980).
Transient		(1) A pulse dampened oscillation or other temporary phenomena occurring in a system prior to reaching a steady-state condition (McGraw-Hill, 1974). (2) See flow, unsteady.
Transmissibility coefficient		(The use of the term transmissibility has been replaced by transmissivity).
Transmissivity		The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths (Lohman and others, 1972).
Transpiration		The loss of water vapour from plants.
Transport		Conveyance of solutes and particulates in flow systems. See also solute transport and particulate transport.
Turbulent flow		The flow condition in which inertial forces predominate over viscous forces and in which head loss is not linearly related to velocity.
U		
Uncertainty (Assessment of)		The quantification of uncertainty in model results due to incomplete knowledge of model aquifer parameters, boundary conditions, or stresses.
Unconfined		A condition in which the upper surface of the zone of saturation forms a water table under atmospheric pressure (after ASCE, 1985).

Entry	Acronym	Primary Definition
Unconfined aquifer		An aquifer which has a water table.
Underground injection		A "well injection" (40 CFR 144.3; 40 CFR Part 146.3).
Unsaturated flow		The movement of water in a porous medium in which the pore spaces are not filled to capacity with water (after SSSA, 1975).
Unsaturated zone		(1) The zone between the land surface and the water table (ASCE, 1985). (2) The zone between the land surface and the deepest water table which includes the capillary fringe. Water in this zone is generally under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies the water pressure locally may be greater than atmospheric (Lohman and others, 1972). (3) The zone between the land surface and the regional water table. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies the water pressure locally may be greater than atmospheric (NRC, 1985). (4) Means the zone between the land surface and the regional water table. Generally, fluid pressure in this zone is less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies the fluid pressure locally may be greater than atmospheric (10 CFR Part 60.2). (5) The zone between the land surface and the water table. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air and other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the water pressure locally may be greater than atmospheric (10 CFR Part 960.2).

Entry	Acronym	Primary Definition
Upconing		Process by which saline water underlying freshwater in an aquifer rises upward into the freshwater zone as a result of pumping water from the freshwater zone (USGS, 1984).
Upper bound (model)		The most unfavorable conditions compatible with the available data about the system. The upper bound is conservative, but realistically conservative.
V		
Vadose Zone		See unsaturated zone.
Validation		Absolute confirmation of a model which can explain all stresses and conditions. Never completely achievable. A stronger term than Verification. See Verification.
Valued Ecosystem Component	VEC	The environmental element of an ecosystem that is identified as having scientific, social, cultural, economic, historical, archaeological or aesthetic importance. The value of an ecosystem component may be determined on the basis of cultural ideals or scientific concern. Valued ecosystem components that have the potential to interact with project components should be included in the assessment of environmental effects.
Velocity, average interstitial		The average rate of groundwater flow in interstices expressed as the product of hydraulic conductivity and hydraulic gradient divided by the effective porosity, (after Lohman and others, 1972). Synonymous with average linear groundwater velocity or effective velocity.
Viscosity		The property of a fluid describing its resistance to flow. Units of viscosity are Newton-seconds per metre squared or Pascal-seconds. Viscosity is also known as dynamic viscosity.
Verification		A test of the integrity of a model by checking if its predictions reasonably match the observations of a reserved dataset, deliberately excluded from consideration during calibration.
Void		See interstice.

Entry	Acronym	Primary Definition
Void ratio		The ratio of (a) the volume of void space to (b) the volume f solid particles in a given soil mass (ASTM, 1980).
Volatiles		Substances with relatively large vapor pressures. Many organic substances are almost insoluble in water so that they occur primarily in a gas phase in contact with water, even though their vapor pressure may be very small.
Von Neumann criteria		A condition specifying the maximum size of timestep needed to avoid numerical oscillations in solute advection-dispersion simulations. The criteria states that the time step should be less than the ratio of the grid spacing squared divided by three times the dispersion coefficient.
W		
Water balance model		See Water Budget
Water budget		A summation of inputs, outputs, and net changes to a particular water resource system over a fixed period.
Water content		The amount of water lost from the soil after drying it to constant weight at 1050C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil (ASTM, 1980). See also moisture content.
Water-holding capacity		See specific retention.
Watershed		All lands enclosed by a continuous hydrologic-surface drainage divide and lying upslope from a specified point on a stream.

Entry	Acronym	Primary Definition
Water table		(1) The upper surface of a zone of saturation except where that surface is formed by a confining unit (after Lohman, 1972). (2) The upper surface of the zone of saturation on which the water pressure in the porous medium equals atmospheric pressure. (3) Means that surface in a groundwater body at which the water pressure is atmospheric (10 CFR Part 60.2). (4) That surface in a body of groundwater at which the water pressure is atmospheric (10 CFR Part 960.2). (5) Upper surface of a zone of saturation, where the body of ground water is not confined by an overlying impermeable zone (30 CFR Part 701.5 and 710.5).
Water-table aquifer		See unconfined aquifer.
Water year		(USGS) The 12-month period October 1, for any given year through September 30, of the following year. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1999 is called the "1999" water year.
Weir		A wall or plate placed in an open channel and used to measure the flow of water. The depth of the flow over the weir can be used to calculate the flow rate, or a chart or conversion table may be used.
Well		A bored, drilled or driven shaft, or a dug hole, whose depth is greater than the largest surface dimension (40 CFR 144.3 and 40 CFR 146.3).
Well, fully penetrating		A well drilled to the bottom of the aquifer, constructed in such a way that it withdraws water from the entire thickness of the aquifer.
Well, partially penetrating		A well constructed in such a way that is draws water directly from a fractional part of the total thickness of the aquifer. The fractional part may be located at the top or bottom or anywhere in between in the aquifer.

Entry	Acronym	Primary Definition
Well screen		A tubular device with either slots, holes, gauze, or continuous wire wrap; used at the end of a well casing to complete a well. The water enters the well through the well screen.
Well development		The process whereby a well is pumped or surged to remove any fine material that may be blocking the well screen or the aquifer outside the well screen.
Well efficiency		The ratio of idealized drawdown in the well, where there are no losses resulting from well design and construction factors, to actual measured drawdown in the well.
Well field		Area containing one or more wells that produces usable amount of water.
Well injection		The subsurface emplacement of "fluids" through a bored, drilled, or driven "well", or through a dug well, where the depth of the dug well is greater than the largest surface dimension (40 CFR 144.3 and 40 CFR 146.3). 28
Well Monitoring		The measurement, by on-site instruments or laboratory methods, of the quality of water in a well.
Withdrawal		The process of taking water from a source and conveying it to a place for a particular type of use.
Worst case (model)		A model that adopts the most extreme parameters conceivable – even though there are no data to support the likelihood of such extreme values occurring. The worst case model may be considered to be extremely or even unrealistically conservative.
X		
Y		
Yield		The quantity of water (expressed as a rate of flow- GPM, GPH, GPD, or total quantity per year) that can be collected for a given use from surface or groundwater sources. The yield may vary with the use proposed, with the plan of development, and also with economic considerations.

Entry	Acronym	Primary Definition
Yield, safe		The amount of naturally occurring groundwater that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native groundwater quality or creating an undesirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in discharge that is due to the decline in head caused by pumping.
Yield, sustainable		That proportion of the long term average annual recharge which can be extracted each year with causing unacceptable impacts on groundwater users or the environment.
Z		
Zone of influence	ZOI	The area surrounding a pumping well within which the water table or Potentiometric Surfaces has been changed due to ground-water withdrawal.

APPENDIX A

REFERENCE GUIDELINES AND STANDARDS

REFERENCE GUIDELINES AND STANDARDS

Several existing guidelines on groundwater modelling from various jurisdictions were reviewed in preparation of these guidelines, including:

- "*Fundamentals of Ground-Water Modelling*" - US Environmental Protection Agency, USA (US EPA, 1992)
- "*Groundwater Hydrology*" - US Army Corps of Engineers, USA (USACE, 1999)
- "*Guide to Good Practice for the development of Conceptual Models and the Selection and Application of Mathematical Models of Contaminant Transport Processes in the Subsurface*" - National Groundwater and Contaminated Land Centre, UK (NGCLC, 2001)
- "*Groundwater Flow Modelling Guideline*" - Murray-Darling Basin Commission, Australia (MDBC, 2001)
- *"Groundwater Model Audit Guidelines*" - Ministry for the Environment, NZ (NZMoE, 2001) "*Groundwater Modelling Guidance*" - Michigan Department of Environmental Quality, USA (MDEQ, 2002)
- "*Guidelines for Evaluating Groundwater Flow Models*" - US Geological Survey (USGS, 2004)

- ASTM guidelines on groundwater modelling:
    - "*Standard Guide for Selecting a Groundwater Modelling Code*" ASTM D6170 - 97 (ASTM, 2010a)
    - "*Standard Guide for Application of a Groundwater Flow Model to a Site-specific Problem*" ASTM D5447 - 04 (ASTM, 2010b)
    - "*Standard Guide for Developing Conceptual Site Models for Contaminated Sites*" ASTM E1689 - 95 (ASTM, 2008a)
    - "*Standard Guide for Defining Boundary Conditions in Groundwater Flow Modelling*" ASTM D5609 - 94 (ASTM, 2008b)
    - "*Standard Guide for Defining Initial Conditions in Groundwater Flow Modelling*" ASTM D5610 - 94 (ASTM, 2008dc
    - "*Standard Guide for Conducting a Sensitivity Analysis for a Groundwater Flow Model Application*" ASTM D5611 - 94 (ASTM, 2008d)
    - "*Standard Guide for Comparing Groundwater Flow Model Simulations to Site-specific Information*" ASTM D5490 - 93 (ASTM, 2008e)
    - "*Standard Guide for Calibrating a Groundwater Flow Model Application*" ASTM D5981 - 96 (ASTM, 2008f)
    - "*Standard Guide for Documenting a Groundwater Flow Model Application*" ASTM D5718 - 95 (ASTM, 2006a)
    - "*Standard Guide for Subsurface Flow and Transport Modelling*" ASTM D5880 - 95 (ASTM, 2006b)

APPENDIX B

REFERENCE TEXTBOOKS

REFERENCE TEXTBOOKS

Anderson, M.P., & Woessner, W.W. (1992). **Applied Groundwater Modelling: Simulation of Flow and Advective Transport**. San Diego, CA: Academic Press, Inc.

Appelo C.A.J. and D. Postma (2009) **Geochemistry, Groundwater and Pollution**, (2nd ed.). CRC Press, Boca Raton, FL, USA

Bear, J. (1972)**. Dynamics of Fluids in Porous Media**. American Elsevier Pub. Co.

Bear, J., & Cheng, A.H.D. (2010). **Modelling Groundwater Flow and Contaminant Transport (Theory and Applications of Transport in Porous Media)**. Springer.

Domenico, P.A, & Schwartz, W. (1990). **Physical and Chemical Hydrogeology** (2nd ed.). New York: Wiley & Sons.

Fetter, C.W. (2001). **Applied Hydrogeology** (4th ed.). Prentice Hall Inc.

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Harr, M.E. (1987) **Reliability-Based Design in Civil Engineering**. McGraw-Hill, NY.

Healy, R.W., & Scanlon, B.R. (2010). **Estimating Groundwater Recharge**. Cambridge University Press.

Hill, M.C., & Tiedeman, C.R. (2007). **Effective Groundwater Model Calibration: With Analysis of Data, Sensitivities, Predictions, and Uncertainty**. Hoboken, NJ: Wiley & Sons.

Schwartz, F.W., & Zhang, H. (2002). **Fundamentals of Ground Water**. Toronto: Wiley & Sons.

Spitz, K. & Moreno, J. (1996). **A Practical Guide to Groundwater and Solute Transport Modeling**. New York: John Wiley.

Todd, D.K., & Mays, L.W. (2004). **Groundwater Hydrology** (3rd ed.). Wiley & Sons.

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APPENDIX C-1

CASE STUDY 1 – OPEN PIT MINE

REPORT NO. 194001

Case Study 1

Open Pit Mine in North Central British Columbia

Table of Contents

C1-1 PROJECT OVERVIEW

Case Study 1 is situated in north central B.C. on the plateau between the Coast Mountain and Rocky Mountain ranges, just north of the town of Fort St. James. The open pit project will recover upwards of 60,000 tonnes per day from the copper-gold deposit with a projected mine life of approximately 20 years.

The mine site ("Site") occupies a valued ecosystem comprising fish-bearing creeks and small lakes hosted in geologic materials indicative of a glacial valley. The main project components will include a two-stage open pit development, a prominent tailings storage facility (TSF), on-site crushing and concentrator plants, as well as a concentrate load-out facility (Figure 1).

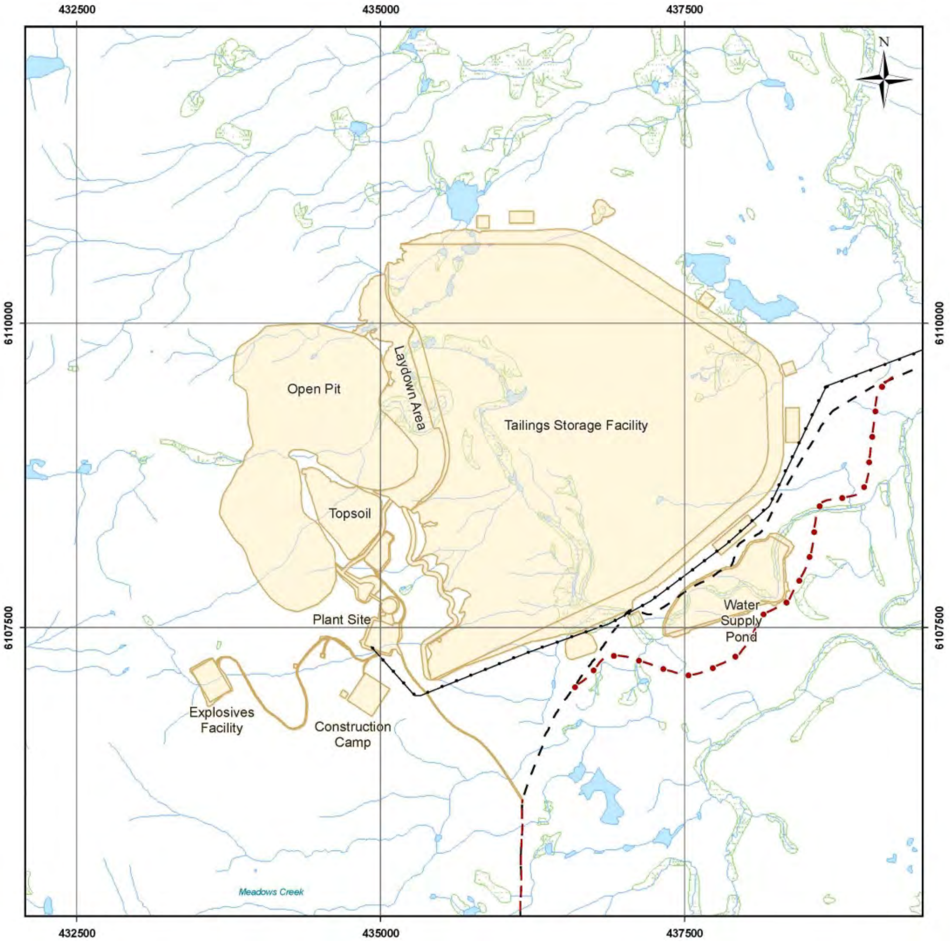


Figure 1: Mine site layout for Case Study 1

Development of the open pits will induce inflow to the pit and the operation of the TSF will likely result in seepage of mine-affected water to the environment. A numerical groundwater modelling effort was undertaken to assess the impacts of these activities on the receiving environment.

C1-2 MODELLING OBJECTIVES

During the application process for an environmental assessment certificate, the Proponent and stakeholders identified groundwater and surface waters as valued ecosystem components (VECs). Subsequently, numerical modelling was undertaken to address the following areas of concern:

- Baseline hydrogeology for the project area, including:
  - Verification of the Site water balance model
  - Interpretation of integrated groundwater and surface water systems
  - Indication of the groundwater flow pattern
- Inflows to the proposed open pit development
- Seepage from the proposed TSF

The regional baseline groundwater flow model would be created initially, and later modified to address the issues of open pit inflow and TSF seepage.

C1-3 DATA REVIEW

Data used to develop the Site conceptual model included information from borehole drilling logs and geologic mapping, sourced primarily from previous field investigations.

The data used to develop the baseline regional groundwater model comprised groundwater elevations, aquifer hydraulic test results, and observed flows. Additional flow estimates were obtained from the site-wide baseline water balance that was completed as part of this modelling exercise.

Limited climate data from the Site was calibrated to local municipal datasets to generate a synthetic series for the Site. This data was used for water balance modelling and for assigning recharge to the numerical groundwater model.

C1-4 CONCEPTUAL MODEL

The Proponent proposed that the objectives could be met by both analytical and numerical modelling approaches. An analytical solution for fault zone contributions to pit inflow, for example, could be used to support a more rigorous numerical solution. Furthermore, both 2D and 3D methods could be employed for modelling, depending on the objective and the complexity of the problem.

The three-dimensional finite difference code MODFLOW-SURFACT was selected for baseline modelling for two primary reasons:

- The code allows for verification that the groundwater recharge, storage, and discharge as defined by the site-wide water balance satisfies groundwater flow theory, and
- The code employs an updated wetting/drying function which minimizes convergence problems typically associated with MODFLOW simulations in steep terrain with steep groundwater gradients.

Auxiliary software tools were also used to facilitate the model set-up and interpretation of results, including:

- Geographic Information Systems (GIS) packages,
- Contour plotting software, and
- Database management programs

For the determination of pit inflow, both analytical and numerical solutions were used.

TSF seepage was modeled first with a 2D cross-sectional model, before using a modified version of the 3D baseline numerical model to confirm the results.

C1-5 NUMERICAL MODEL SETUP

Baseline Groundwater Flow Model

The boundaries of the baseline groundwater flow model are depicted in Figure 2.

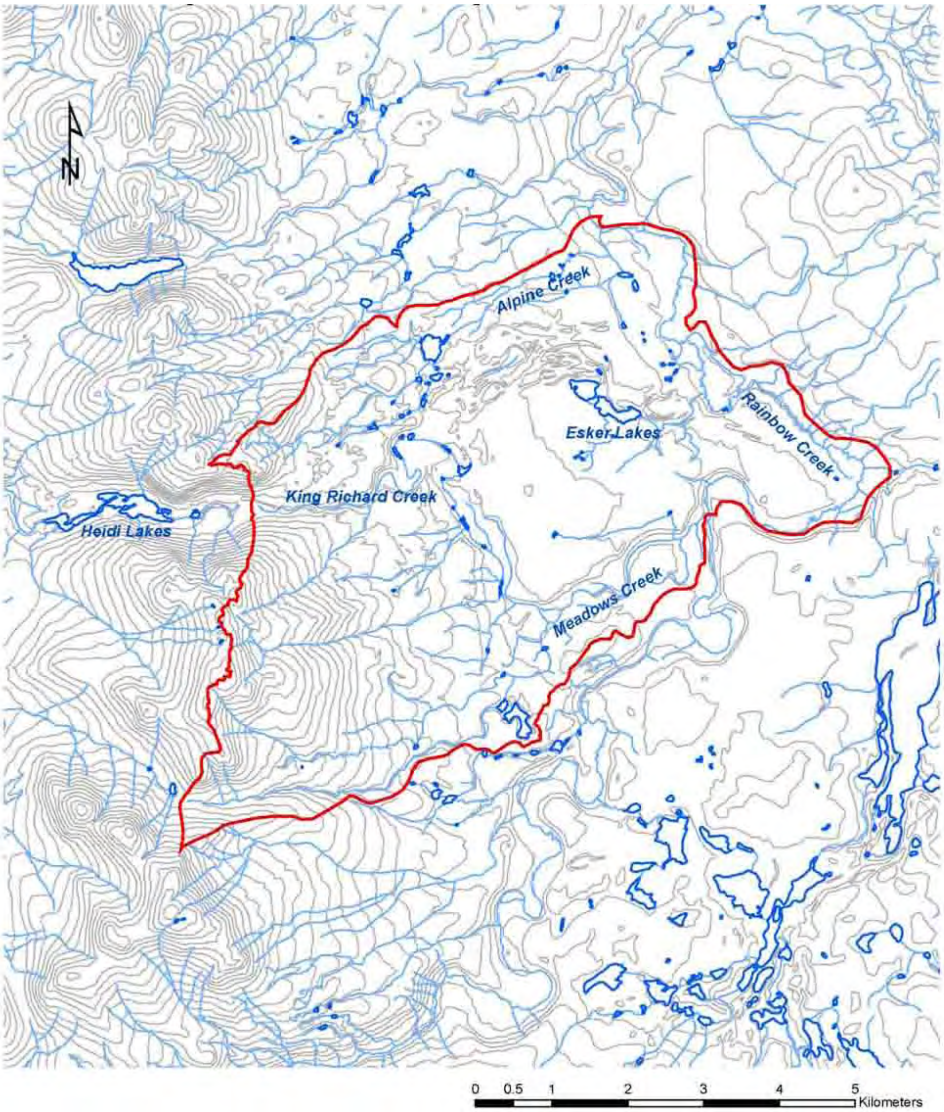
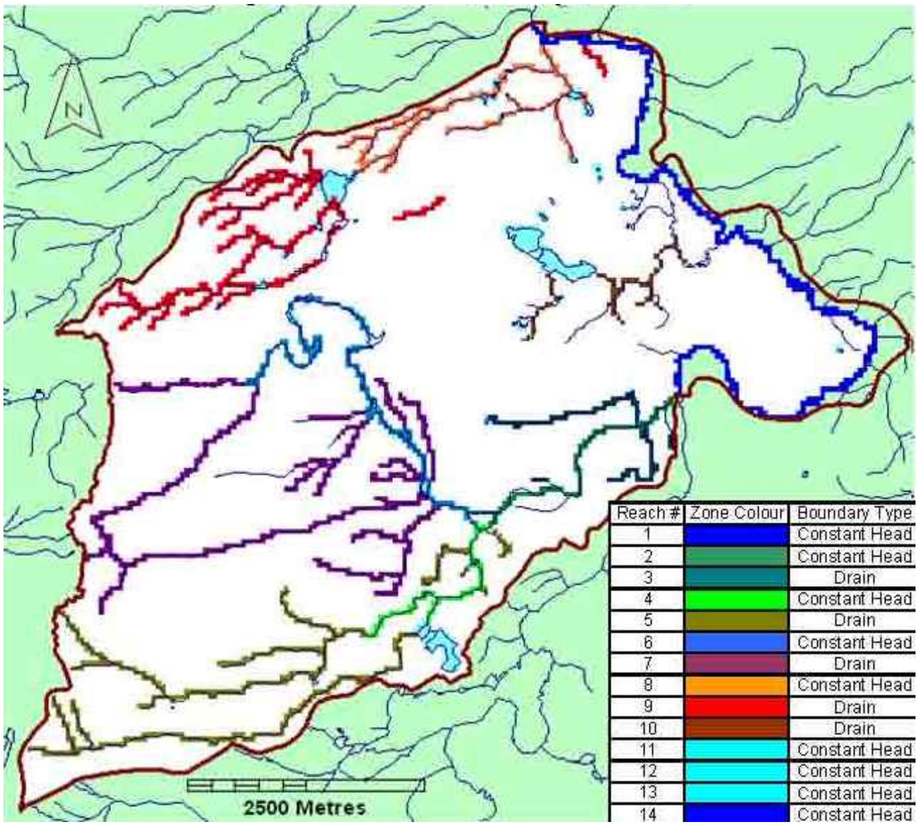


Figure 2: Boundaries of baseline groundwater flow model (red)

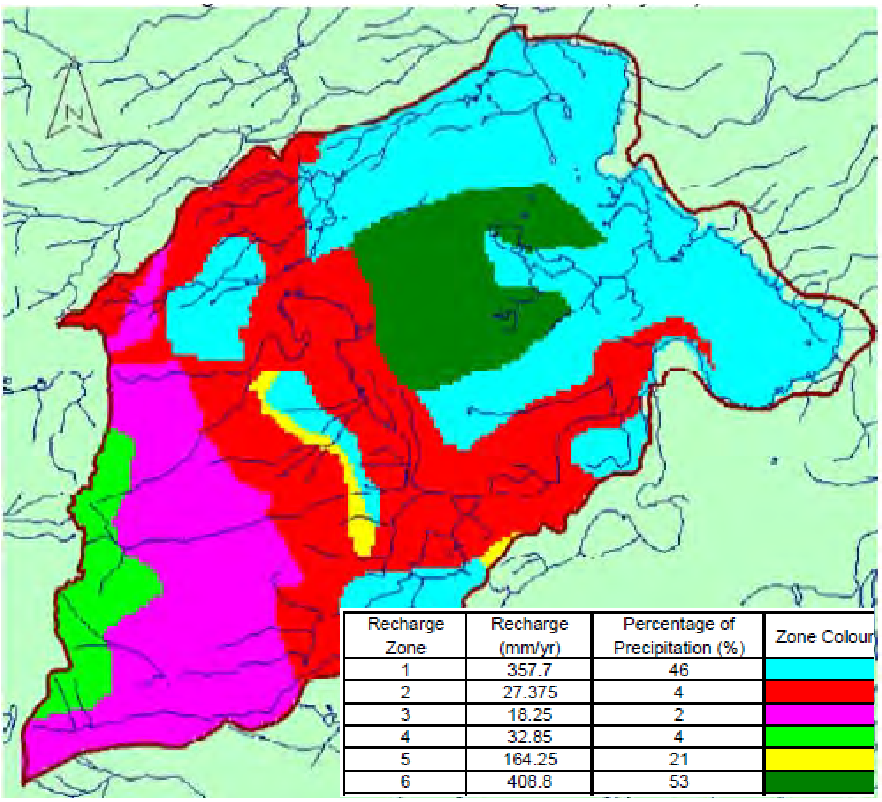
The domain is bounded primarily by the natural groundwater divides formed by creeks to the north, south, and east, and by bedrock topography to the west. The extent of the domain is such that the boundaries are not likely to bias the flow solution.

Creeks, lakes, and ponds were represented as constant head boundaries in the model while ephemeral streams and seeps were simulated with drains (Figure 3). The drains were assigned a constant conductance for all model runs. Aerial (meteoric) recharge was applied to the model according to earlier water balance modelling for the Site. The distribution of recharge zones across the model domain is shown in Figure 4.



Reach #	Zone Colour	Boundary Type
1	🟦	Constant Head
2	🟩	Constant Head
3	🟦	Drain
4	🟩	Constant Head
5	🟫	Drain
6	🟦	Constant Head
7	🟪	Drain
8	🟧	Constant Head
9	🟥	Drain
10	🟫	Drain
11	🟦	Constant Head
12	🟦	Constant Head
13	🟦	Constant Head
14	🟦	Constant Head

Figure 3 - Baseline boundary conditions



Recharge Zone	Recharge (mm/yr)	Percentage of Precipitation (%)	Zone Colour
1	357.7	46	🟦
2	27.375	4	🟥
3	18.25	2	🟪
4	32.85	4	🟩
5	164.25	21	🟨
6	408.8	53	🟩

Figure 4: Zones of recharge for the baseline model

The finite difference grid was uniformly distributed across the domain. The domain comprises approximately 180 rows and 200 columns, encompassing an area of 40 km^2. Vertically, the model was discretized into five hydrostratigraphic layers representing glacial outwash, till, and bedrock (Figure 5). All layers were modeled as confined layers to avoid convergence issues due to low recharge values and steep topography.

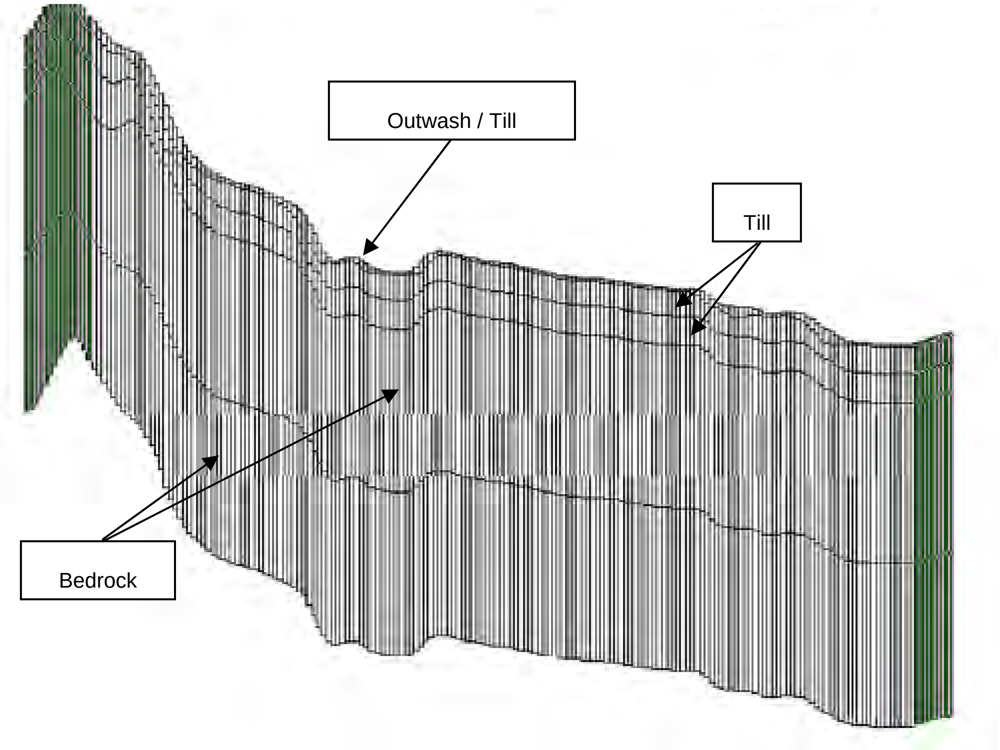


Figure 5: Vertical discretization of model domain

The model was first run with steady state conditions to evaluate regional flow and then run with transient conditions to assess groundwater contribution to streamflow under low recharge conditions.

<u>Open Pit Inflow Model</u>

The baseline numerical model was used to estimate pit inflows according to the modelling objectives. The setup of this model is identical to that of the baseline model in terms of model domain, discretization, and initial conditions; however, boundary conditions in the area of the open pit (surface water features) were removed from the model. All aquifer properties were identical to the baseline model.

Dewatering of the open pit was simulated using MODFLOW by assigning pumping wells to the pit area which caused the simulated water level to be lowered according to the mine plan. The model was run at steady state at three distinct times during the mine life. Figure 6 shows the drawdown contours after 7 years of mining.

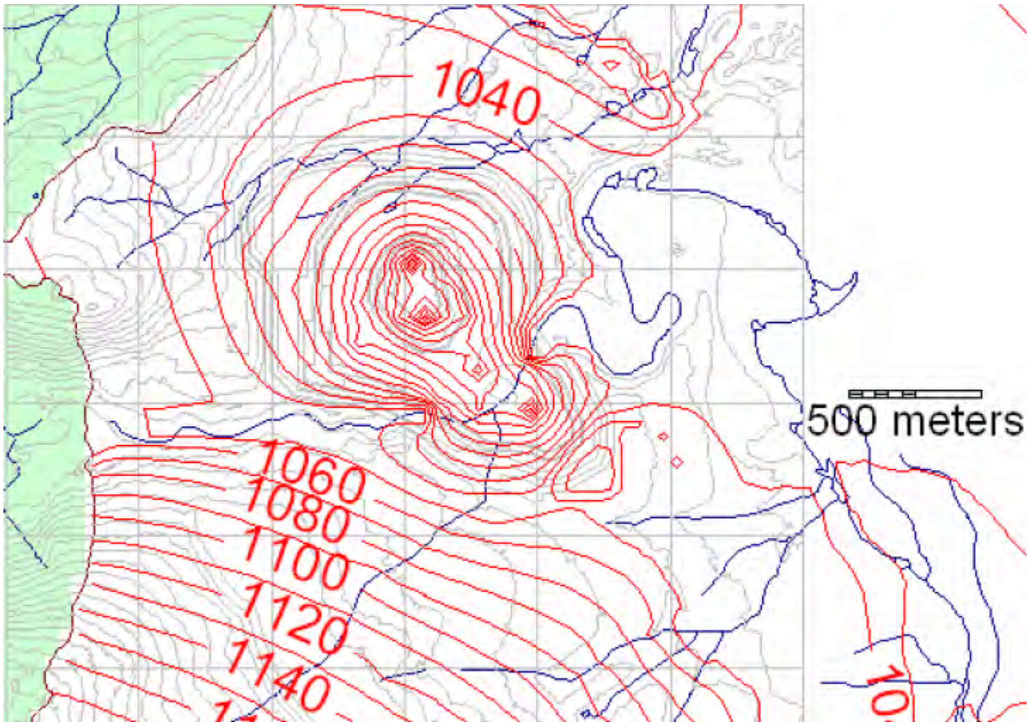


Figure 6: Drawdown contours (red) in the vicinity of the open pit after 7 years of mining

The influence of the TSF on pit flows was not explicitly modeled at this stage, but covered later in the TSF-specific modelling phase. The results from the TSF modelling were subsequently used to verify the assumptions regarding TSF contribution to the pit inflow model.

As fault zones were intersected during drilling in the open pit area, a Darcy based analytical approach was used to conservatively estimate the discharge from an intersecting fault zone. This value was summed with the numerical inflow calculation and the estimate of TSF seepage contribution to determine a conservative pit inflow estimate.

<u>Tailings Storage Facility (TSF) Seepage Model – 2D Analysis</u>

Prior to setting up the three dimensional TSF model, a series of two dimensional VADOSE/W models were created to meet the following objectives:

- Estimate seepage using a range of hydraulic conductivity values for the glacial foundation materials (sensitivity analysis)
- Identify key flow pathways
- Estimate groundwater recharge under unsaturated conditions

VADOSE/W was selected for its applicability to unsaturated flow problems. The 2D model incorporates hydrostratigraphic units consistent with the baseline model and materials representing the gradation of tailings and TSF structural elements (i.e. the core, filter, and shell). The three sections chosen for modelling are presented in Figure 7.

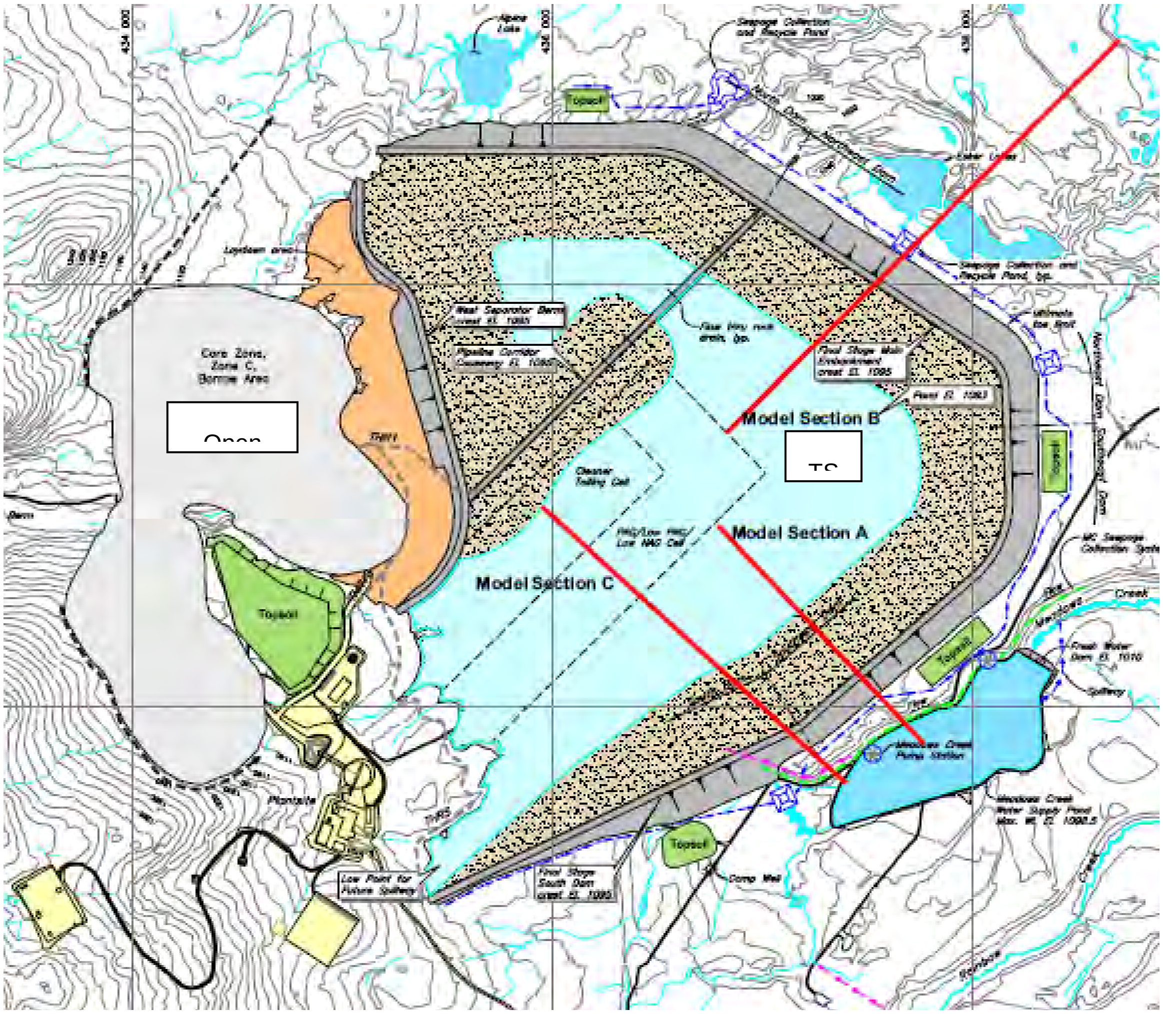


Figure 7: Section alignments for 2D VADOSE/W modelling (red lines)

The sections represent the most direct pathways to sensitive receptors downstream of the TSF. Section B is shown in Figure 8 as an example of the TSF elements and hydrostratigraphy.

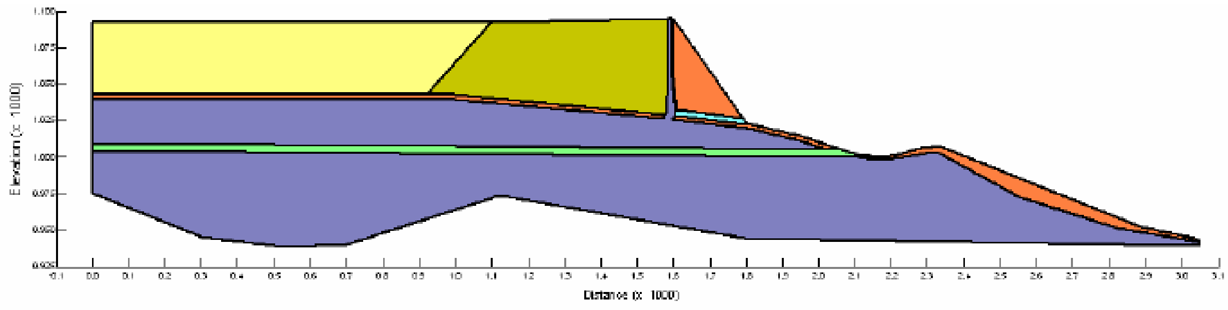


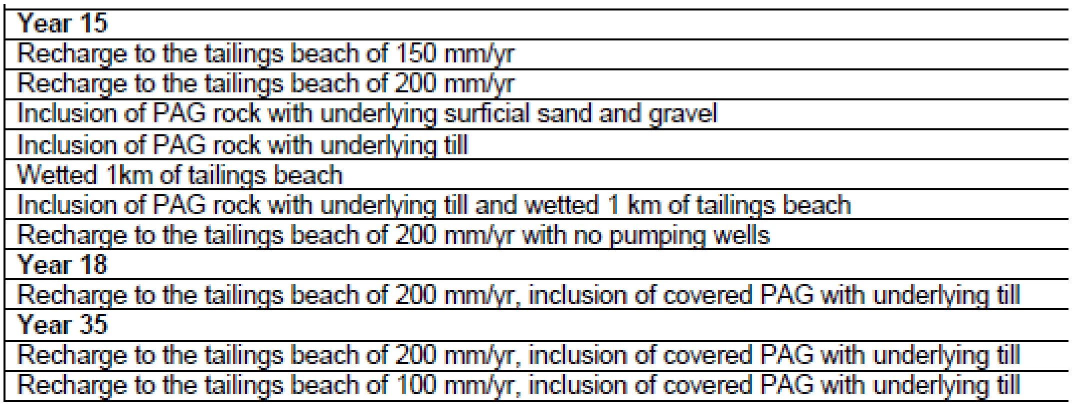
Figure 8: Model Section B in VADOSE/W

Boundary conditions for the VADOSE/W sections comprise recharge to the upper surface and constant head boundaries representing the tailings pond level and the surface of downstream water bodies. All models were run in transient state for at least two years.

Tailings Storage Facility (TSF) Seepage Model – 3D Analysis

Following the 2D seepage modelling, the 3D baseline groundwater model was modified to explicitly include the tailings storage facility. This model included most of the elements of the baseline model but also included layers to represent the tailings materials and refinement of the hydrostratigraphy beneath the TSF based on the VADOSE/W modelling. The model was first run with steady state conditions over a range of recharge and hydrogeologic scenarios at a time period equal to 15 years of operation. Subsequent steady state runs at 18 and 35 years of operation were completed with only the most reasonable hydrogeologic conditions determined from the initial runs. A summary of the runs is provided in Table 1.

Table 1: Simulation runs for 3D numerical model of TSF



Year 15
Recharge to the tailings beach of 150 mm/yr
Recharge to the tailings beach of 200 mm/yr
Inclusion of PAG rock with underlying surficial sand and gravel
Inclusion of PAG rock with underlying till
Wetted 1km of tailings beach
Inclusion of PAG rock with underlying till and wetted 1 km of tailings beach
Recharge to the tailings beach of 200 mm/yr with no pumping wells
Year 18
Recharge to the tailings beach of 200 mm/yr, inclusion of covered PAG with underlying till
Year 35
Recharge to the tailings beach of 200 mm/yr, inclusion of covered PAG with underlying till
Recharge to the tailings beach of 100 mm/yr, inclusion of covered PAG with underlying till

The model domain was decreased in extent to exclude the steep topography west of the mine. This was done to facilitate model convergence. Furthermore, surface water features in the footprint of the TSF were removed and constant head boundaries were used to simulate pumping wells (proposed to be installed in the more transmissive materials beneath the facility).

To account for the open pit, while not explicitly including the excavation in the model, a general head boundary was assigned to the eastern pit boundary in the most transmissive model layer.

The tailings pond was simulated with the MODFLOW-96 river package which permits flow between surface water features and groundwater based on a conductance assigned to the bottom of the surface water body. As two distinct gradations of tailings are to be stored in the TSF, two values of conductance were used for the respective areas of the facility.

Meteoric recharge was simulated at several different rates based on climatic expectations and the degree of exposure of the tailings beach (i.e. wetted beach length, vegetation coverage, and supernatant pond coverage). The type of tailings exposed was also considered as finer grained tailings may inhibit recharge to the subsurface.

The hydrogeologic components of the TSF were assigned typical values of hydraulic conductivity supported by independent laboratory testing. The values of hydraulic conductivity assigned to the TSF components are presented in Figure 9.

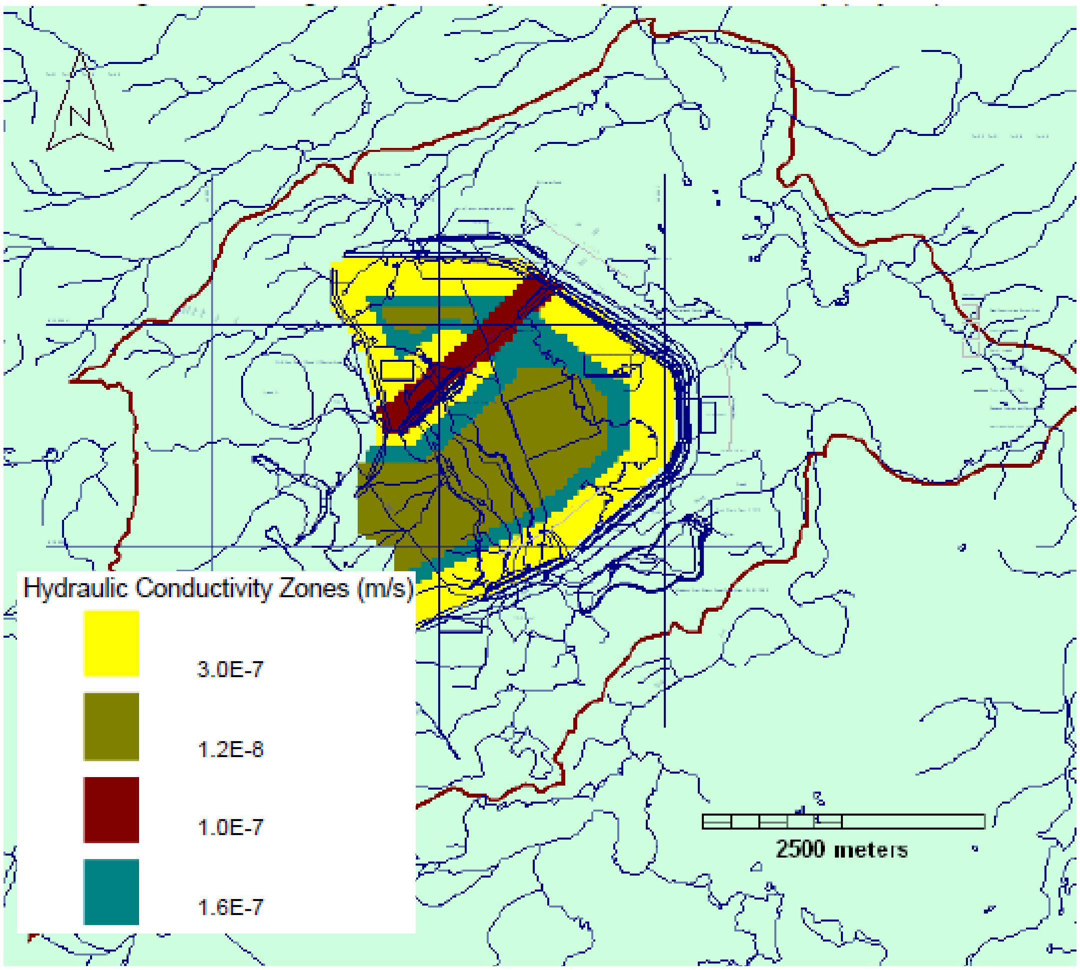


Figure 9: Distribution of hydraulic conductivity in the TSF model

C1-6 MODEL CALIBRATION

Baseline Groundwater Model Calibration

The baseline numerical groundwater model was calibrated to hydraulic head targets and groundwater estimates of flux between sub-catchments from the site-wide water balance. During dry periods (late winter), baseflows were measured and reproduced with the water balance, improving the uniqueness of the solution. In addition to these calibration targets, the following factors were also reviewed at the calibration stage:

- Visual assessment of flow direction, especially in the vicinity of assumed hydrologic divides and imposed boundaries

- Comparison of calculated groundwater head contours to those interpreted from field water level surveys (Figure 10 and Figure 11)
- Quantitative comparison of model recharge values to those derived from the water balance
- Qualitative comparison of as-modeled hydraulic conductivity value to those inferred from aquifer hydraulic testing
- Comparison of the simulated groundwater flow system to the conceptual groundwater flow model

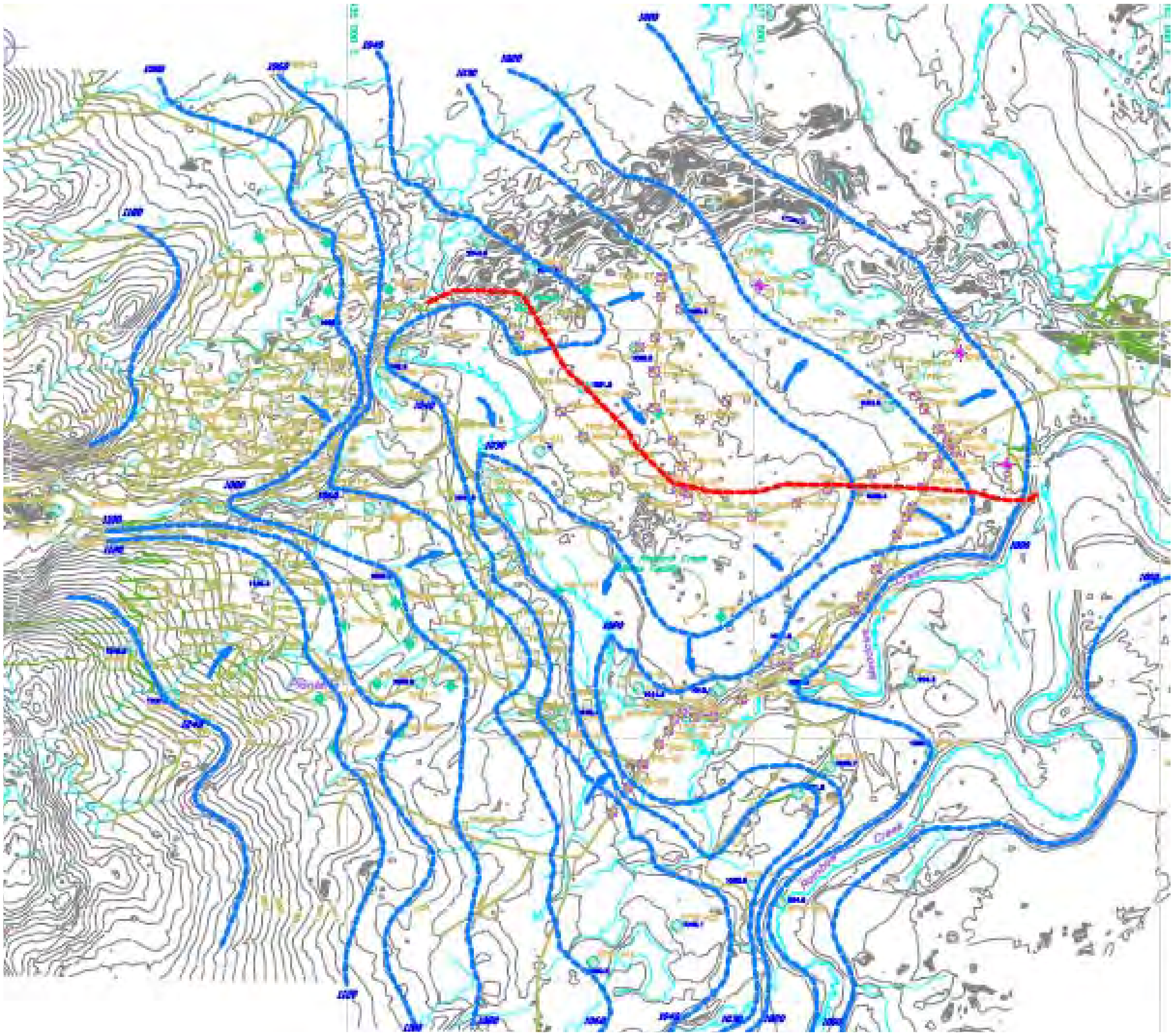


Figure 10: Groundwater level contours (dashed blue) interpreted from field survey. Red dashed line indicates a groundwater divide between two creeks.

The values of recharge and hydraulic conductivity were varied until the calibration targets were met. A comparison of sub-catchment discharge from the water balance model and the numerical groundwater model is presented in Table 2. The comparison of measured and simulated groundwater heads is presented in Figure 11.

Table 2: Comparison of water balance discharge to calibrated numerical model discharge

Subcatchment	Modeled Groundwater Discharge (m^3/day)	Calculated Groundwater Discharge (m^3/day)	Percent Difference
Area3	5175	5233	-1.1
Area4	6213	6036	2.9
Area5			
Area10	6142	6301	-2.5
Total	17530	17570	-0.2

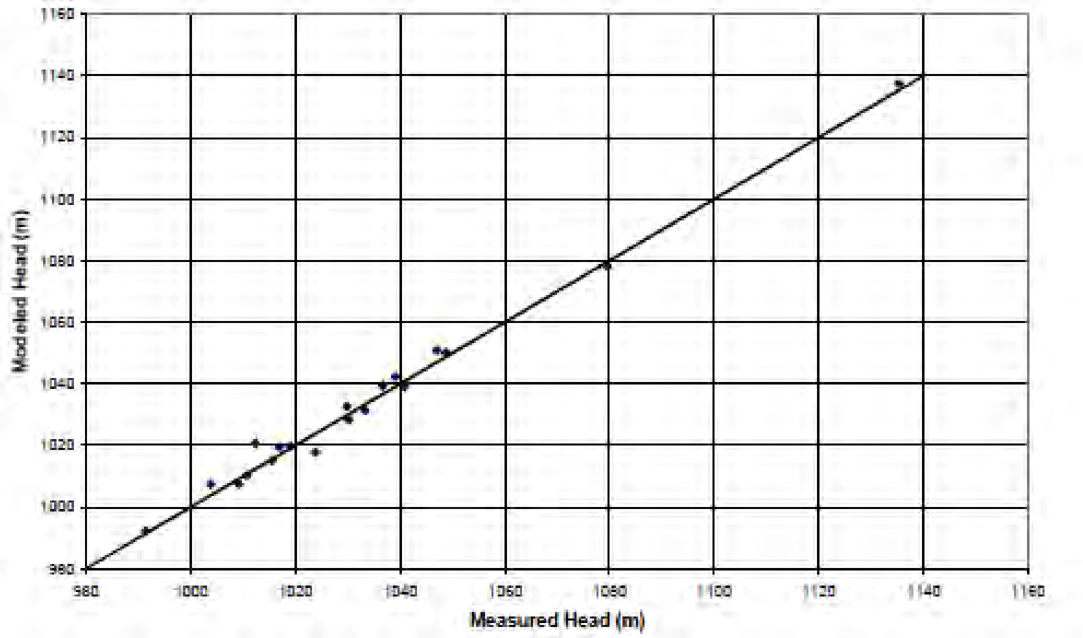


Figure 011: A comparison of measured and simulated groundwater heads

Note that the measured head data presented in Figure 11 is an assimilation of historic and more recent water levels which are not necessarily temporally or spatially consistent. Furthermore, the spatial distribution of these monitoring points across the Site is not presented. However, it appears as though the model is reasonably well calibrated to observed field conditions.

Pit Inflow Model Calibration

No additional calibration was undertaken for the pit inflow modelling.

TSF Seepage Model Calibration

No additional calibration was undertaken for the 2D or 3D modelling. Generally, material properties and boundary conditions from the baseline model were assumed.

C1-7 MODEL PREDICTIONS & SENSITIVITY ANALYSES

Baseline Groundwater Model Results

The result of the baseline groundwater flow model is illustrated by the flow field in Figure 12. Generally, groundwater flow divides are shown to follow topographic highs and surface water features act as groundwater discharge zones.

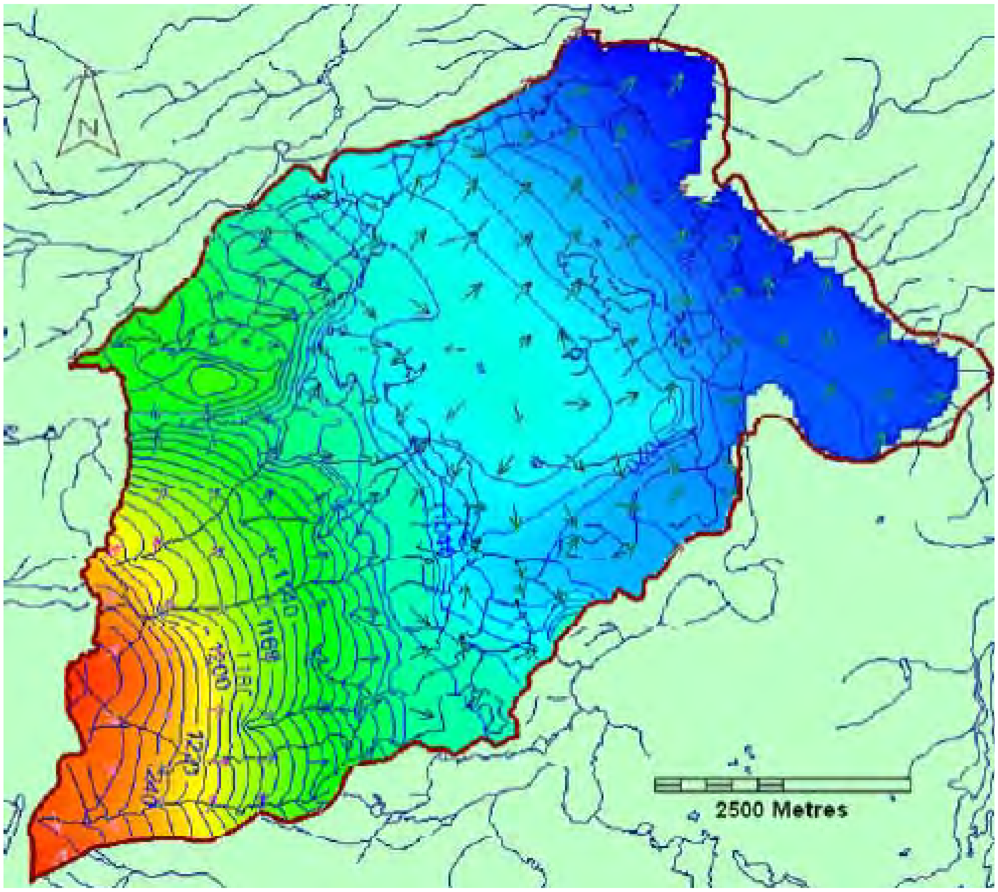


Figure 12: Simulated hydraulic head and groundwater flow vectors

The baseline model provides the relative depth to water table for the highlands and lowlands of the project site as well as the direction and magnitude of hydraulic gradients.

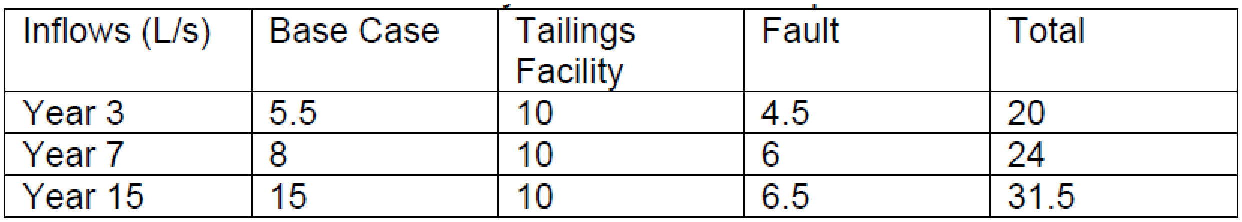
The steady state flow solution was used to perform a particle tracking exercise which is discussed in the Transport Modelling section.

Furthermore, the results of the baseline numerical model were used to verify the groundwater discharge assumptions used in the site-wide water balance.

Pit Inflow Model Results

A combination of steady state numerical modelling, analytical estimation, and discharge estimates from a separate numerical model (that explicitly included the TSF) were used to estimate pit inflow over the mine life. The results are provided in Table 3.

Table 3: Pit inflow estimates based on numerical and analytical methods



Inflows (L/s)	Base Case	Tailings Facility	Fault	Total
Year 3	5.5	10	4.5	20
Year 7	8	10	6	24
Year 15	15	10	6.5	31.5

These results are based on conservative assumptions regarding the location and transmissivity of an intersecting fault zone as well as the discharge contributions from the adjacent TSF.

The steady state results were interpolated using a Theis solution to provide estimates of the annual pit inflow rates (Figure 13).

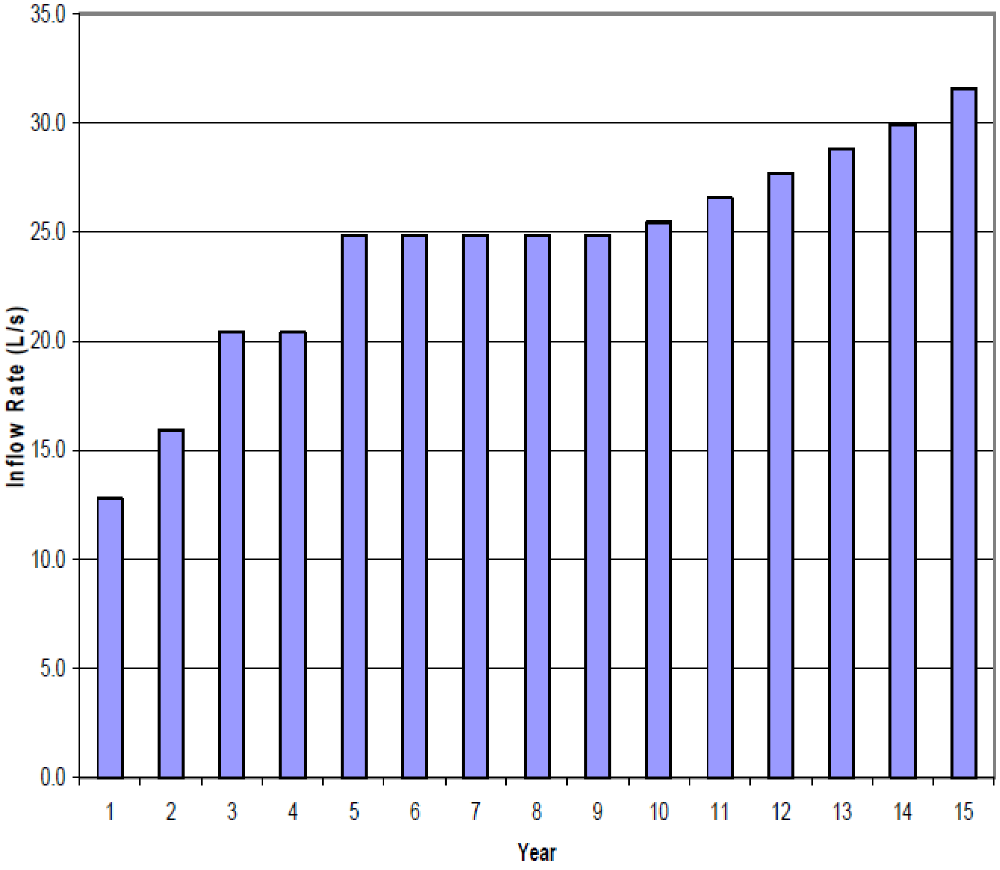
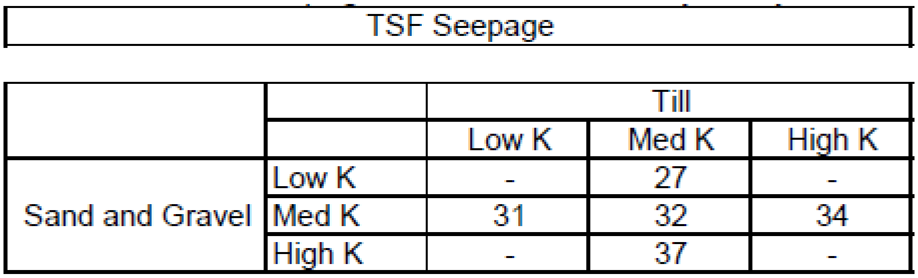


Figure 13: Annual pit inflow rates

TSF Seepage Model Results

Both 2D and 3D modelling were conducted to provide estimates of seepage from the tailings storage facility. For the 2D modelling, a sensitivity analysis was conducted with respect to the range of plausible hydraulic conductivity values assigned to the materials beneath the TSF. Prominent units were assigned plausible high, medium, and low hydraulic conductivity values and plausible scenarios were evaluated (Table 4).

Table 4: Results of 2D seepage analysis (values in L/s)



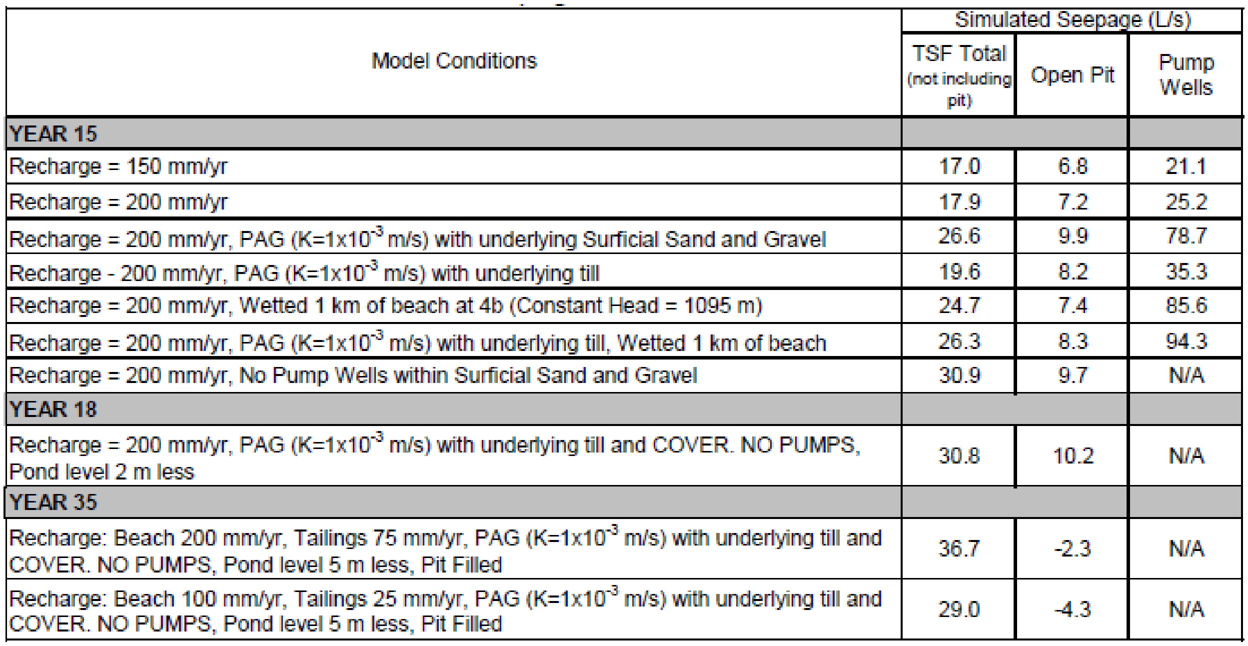
TSF Seepage

		Till		
		Low K	Med K	High K
Sand and Gravel	Low K	-	27	-
	Med K	31	32	34
	High K	-	37	-

Values for flow to pumping towers within the TSF were also determined and reported for the various sensitivity runs. The 2D VADOSE/W results were acknowledged as overestimates, as radial flow is not accounted for in section and recharge is overestimated when summing the sections over the area of the TSF.

The results of the 3D numerical model are presented Table 5. The results cover a range of plausible scenarios with respect to variations in meteoric recharge, tailings characteristics, beach geometry, foundation materials, internal pumping, and pond management.

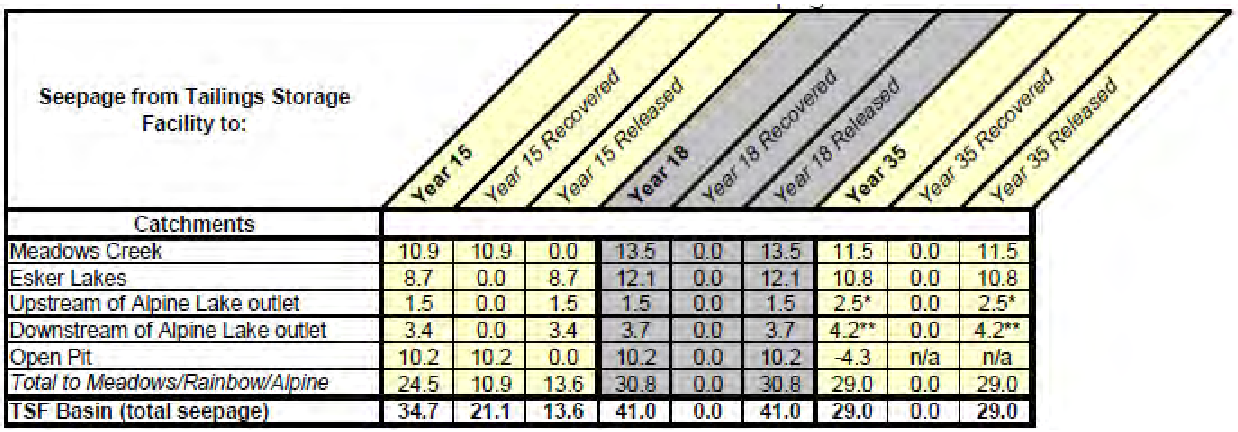
Table 5: TSF seepage estimates based on 3D numerical modelling



Model Conditions	Simulated Seepage (L/s)		
	TSF Total (not including pit)	Open Pit	Pump Wells
YEAR 15			
Recharge = 150 mm/yr	17.0	6.8	21.1
Recharge = 200 mm/yr	17.9	7.2	25.2
Recharge = 200 mm/yr, PAG ($K=1x10^{-3}$ m/s) with underlying Surficial Sand and Gravel	26.6	9.9	78.7
Recharge - 200 mm/yr, PAG ($K=1x10^{-3}$ m/s) with underlying till	19.6	8.2	35.3
Recharge = 200 mm/yr, Wetted 1 km of beach at 4b (Constant Head = 1095 m)	24.7	7.4	85.6
Recharge = 200 mm/yr, PAG ($K=1x10^{-3}$ m/s) with underlying till, Wetted 1 km of beach	26.3	8.3	94.3
Recharge = 200 mm/yr, No Pump Wells within Surficial Sand and Gravel	30.9	9.7	N/A
YEAR 18			
Recharge = 200 mm/yr, PAG ($K=1x10^{-3}$ m/s) with underlying till and COVER. NO PUMPS, Pond level 2 m less	30.8	10.2	N/A
YEAR 35			
Recharge: Beach 200 mm/yr, Tailings 75 mm/yr, PAG ($K=1x10^{-3}$ m/s) with underlying till and COVER. NO PUMPS, Pond level 5 m less, Pit Filled	36.7	-2.3	N/A
Recharge: Beach 100 mm/yr, Tailings 25 mm/yr, PAG ($K=1x10^{-3}$ m/s) with underlying till and COVER. NO PUMPS, Pond level 5 m less, Pit Filled	29.0	-4.3	N/A

Impacts to the receiving environment were also quantified using the 3D seepage model. Table 6 provides estimates of seepage to the local environment and open pit over time.

Table 6: Estimates of TSF seepage to the local environment and open pit



Seepage from Tailings Storage Facility to:	Year 15	Year 15 Recovered	Year 15 Released	Year 18	Year 18 Recovered	Year 18 Released	Year 35	Year 35 Recovered	Year 35 Released
Catchments									
Meadows Creek	10.9	10.9	0.0	13.5	0.0	13.5	11.5	0.0	11.5
Esker Lakes	8.7	0.0	8.7	12.1	0.0	12.1	10.8	0.0	10.8
Upstream of Alpine Lake outlet	1.5	0.0	1.5	1.5	0.0	1.5	2.5*	0.0	2.5*
Downstream of Alpine Lake outlet	3.4	0.0	3.4	3.7	0.0	3.7	4.2**	0.0	4.2**
Open Pit	10.2	10.2	0.0	10.2	0.0	10.2	-4.3	n/a	n/a
Total to Meadows/Rainbow/Alpine	24.5	10.9	13.6	30.8	0.0	30.8	29.0	0.0	29.0
TSF Basin (total seepage)	**34.7**	**21.1**	**13.6**	**41.0**	**0.0**	**41.0**	**29.0**	**0.0**	**29.0**

C1-8 TRANSPORT MODELLING

MODPATH was used to visualize the travel time of groundwater across the Site. Simulated particles were released from various points of interest and their migration plotted at 30-day intervals (Figure 14).

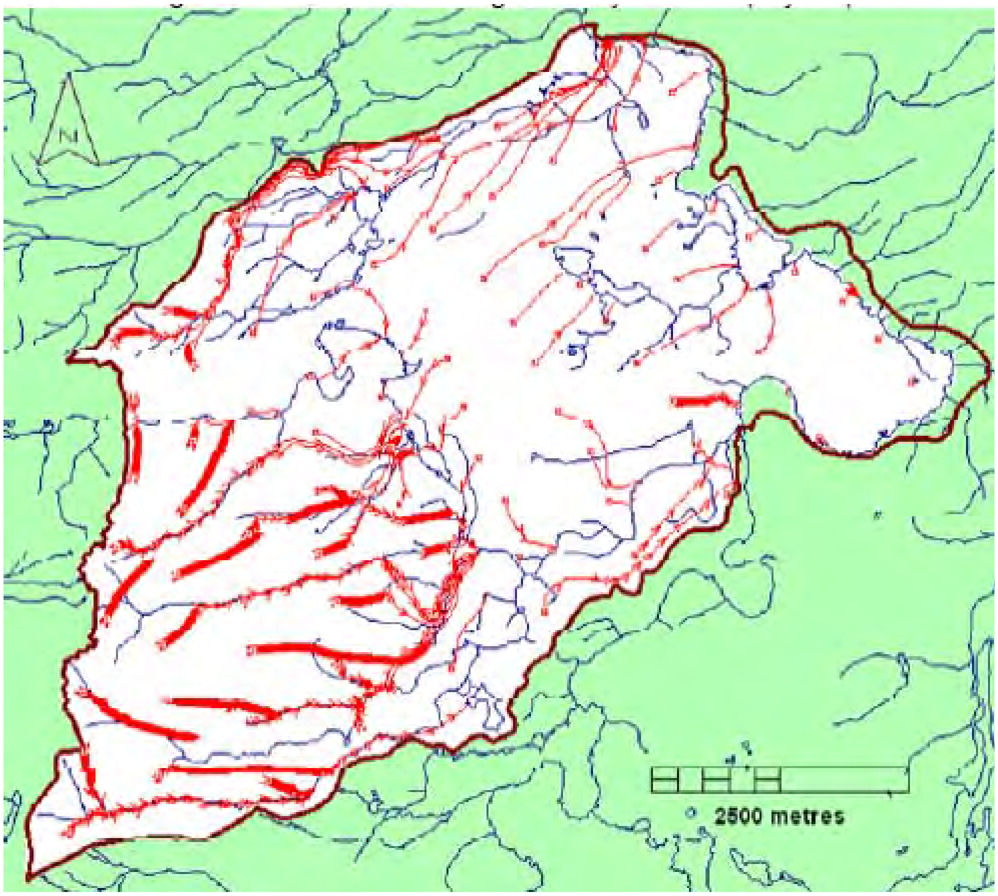


Figure 14: Particle tracking results for baseline groundwater model

No additional transport modelling was undertaken at this stage of application for an environmental assessment certificate.

C1-9 CASE STUDY EVALUATION

Model limitations were not explicit in the model documentation reviewed for this case study, except where addressed by sensitivity analysis or other approaches to uncertainty.

Prior field investigations have been acknowledged in the development of these models and data referenced where appropriate. Generally, the calibration data is limited. Hydraulic testing was conducted to establish hydrogeologic properties; however, the data is limited spatially.

Like most sites in northern British Columbia, the Site likely exhibits complex hydrogeologic conditions that may not be adequately reflected in a conceptual model based on such a limited site data. However, the sensitivity of model predictions to the location of transmissive fault structures has been addressed using a simple, hypothetical, analytical calculation. The conceptual model for this site did incorporate a site-wide water balance for surface and groundwater. Furthermore, the conceptual model was updated during the modelling process to reflect new data from drilling investigations; this conceptual model was applied to more detailed modelling of TSF seepage.

The 3D numerical model code was appropriately selected based on the spatial complexity of the site, including the distribution of hydrostratigraphic units, boundary conditions, and the level of risk of mine-affected groundwater to the receiving environment. Discretization of the model domain appropriately reflected the conceptualization without creating an overly complex model. Analytical solutions were used appropriately for preliminary estimates of flow and to supplement more rigorous numerical modelling. Steady state models were appropriately used to represent various discrete phases of the mine plan and transient flow models were applied for prediction of cumulative seepage effects.

Transport modelling was restricted to pathline analysis with limited comments regarding the results of that analysis and their impact on risk to environmental receptors. The lack of site specific data precluded the use of a more sophisticated transport modelling approach. As a conservative approach, the assumption was made that contaminants would arrive “immediately” in the streams and the predicted impact locations and that there would be no loss of mass along the pathway.

Calibration statistics were reported, however limiting the dataset. While the calibration statistics are generally acceptable, the scarcity of calibration targets leaves uncertainty in the applicability of the model to meet the modelling objectives. An attempt was made to constrain the solution and reduce this uncertainty by making full use of stream flow measurements in order to meet the modelling objectives.

Generally, sensitivity analyses were applied appropriately; however, where a range of results are provided, the selection of the most plausible result is not always clearly justified in the documentation reviewed for this case study (e.g. the selection of most probably TSF seepage scenario after 15 years). In some cases, this results in the exclusion of the most conservative scenario, without documented justification.

While the series of modelling techniques applied in this study have met the modelling objectives, the project would greatly benefit from more hydrogeologic data for calibration to conditions of temporally variable baseline heads, aquifer stresses induced by mine development (e.g. pit dewatering), and the location, orientation, and transmissivity of high permeability features (e.g. especially faults). Water quality and tailings seepage potential could be investigated with predictive transport modelling given data on the physical and chemical nature of the tailings and more detailed construction and management plans for the TSF; however, a conservative mass balance approach was adopted to meet the modelling objectives at this stage of the project.

APPENDIX C-2

CASE STUDY 2 – UNDERGROUND MINE

REPORT NO. 194001

Case Study 2

Underground Mine in Northwestern British Columbia

Table of Contents

C2-1 PROJECT OVERVIEW

Case Study 2 is situated in northwestern British Columbia. The project site (“Site”) comprises glaciated alpine terrain that slopes into a glacial outwash and till valley. Several significant streams and one lake occupy the valley immediately downstream of the Site (Figure 1). The underground mine, as proposed, will produce several thousand tonnes of molybdenum per day with access from one historic adit and one newly driven adit. Waste rock will be processed and used as backfill; hence above-ground, long-term storage facilities will not be required. An ore load-out facility and temporary rock dump will occupy the lower reaches of the Site.

Figure 1: Case Study 2 location map illustrating location of main creeks (blue lines), access roads (red and brown lines) and project site (green switchbacks and red portal)

The operation of the mine will induce groundwater discharge to the underground workings and, as a result, has the potential to adversely impact fish-bearing surface waters by decreasing stream baseflows. Seepage from the mine workings may also threaten surface water and groundwater drinking sources for local residents. Water sampled from the historic adit demonstrates existing elevated molybdenum and arsenic concentrations. Due to the proximity of the project site to residential drinking water sources and fish-bearing habitat, this project carries a high degree of risk to the local receiving environment (high VEC).

The project has been modeled at two levels. First, a detailed numerical model was developed to simulate discharge to the mine workings and changes to groundwater flow and quality over the course of mine development and closure. Secondly, after initial review, the numerical model was updated and the modelling approach refined through improved conceptualization and uncertainty analysis to more confidently quantify the discharge to the underground workings and to assess potential impacts to surface water discharge processes. Furthermore, the improved numerical model was used to simulate the transport of adit seepage over 100 years after mine closure.

C2-2 MODELLING OBJECTIVES

Modelling was undertaken at two distinct periods during the application for an environmental assessment certificate. During the initial modelling stage, the model was used to estimate discharge from the mine workings over the 10 year mine life and for 1000 years post-mining. The purpose of the model was to establish groundwater flow directions and quantities, and to assess the potential for mine-affected groundwater to impact downstream water sources. This initial modelling study was, however, based on very limited data and a relatively simple modelling approach that did not adequately address the high levels of uncertainty encountered. As a result, a second phase of modelling was undertaken.

The objectives of the second, more comprehensive, modelling effort were twofold:

- To provide an updated estimate for discharge to underground workings over time, and
- To assess the impacts of the inflow into the mine on surface water discharge processes, and
- To assess the impacts on well users downhill of the proposed mine.

This second model was constructed on the basis of the initial model but included several key modifications, namely:

- Revision of the model domain to allow interactions between creeks in the adjacent watersheds and the mine,
- Simplification of the representation of mine workings,
- Extensive sensitivity analysis of key parameters, and
- More thorough transient simulations related to all stages of the mine plan

However, it should be noted that the field data supporting the model remained the same.

C2-3 DATA REVIEW

Geologic data were available from the exploration logs of the Proponent and residential well drilling logs from the provincial government. This data aided in the conceptualization of the Site geology and of hydrogeologically significant units. Borehole logs were reviewed to aid in site conceptualization and hydraulic testing was performed in select exploration holes to establish hydraulic properties of the subsurface.

Hydrogeologic data comprises seasonal static water levels from five existing residential wells and from five additional monitoring wells distributed across the watershed. Baseline water quality samples were also analyzed from these wells. Well locations are plotted in Figure 2. The dataset is very limited but spatially distributed across the Site and in downstream receiving environment (upstream of Kathlyn Lake).

Hydraulic testing of the bedrock was accomplished by packer testing in eight exploration holes. However, these tests did not address horizontal anisotropy of hydraulic conductivity. Slug testing was conducted in the shallow alluvium. Seep estimates from the historic adit were also available at the time of model preparation.

No assessments were reported on the nature of bedrock fractures at the site to support assumption of equivalent porous media for the numerical model. There were also no assessments of effective porosity or specific yield of the bedrock units available to the modeller, parameters used to estimate groundwater velocities and travel times.

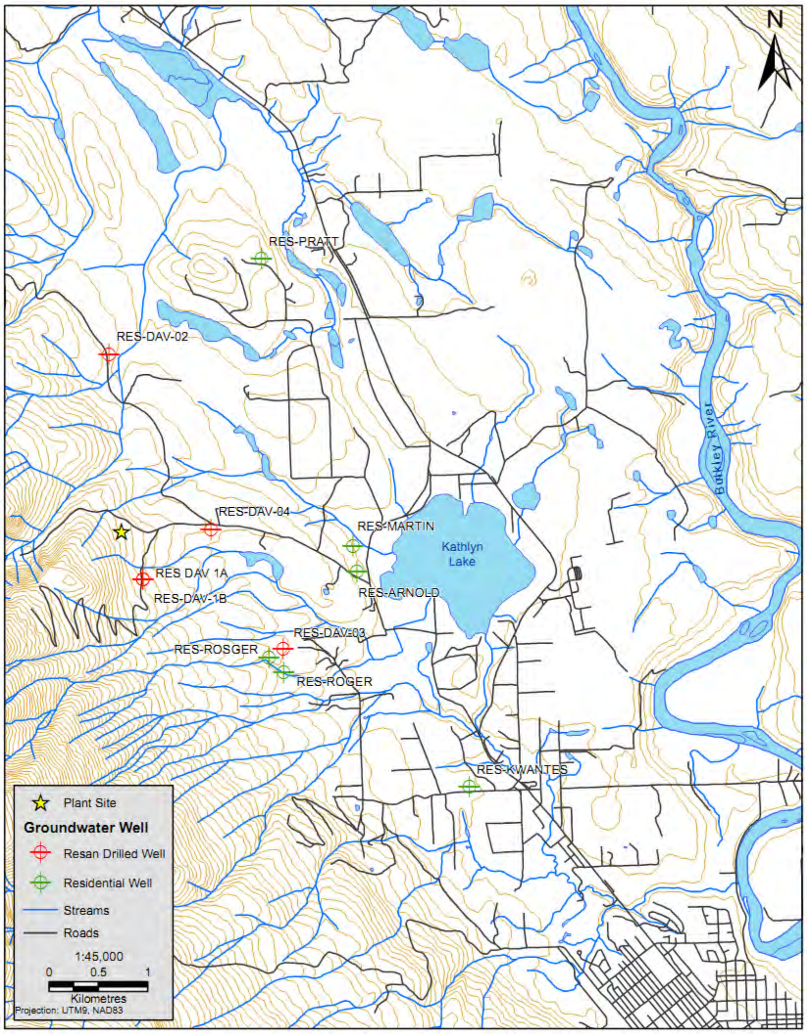


Figure 2: Location of monitoring wells (red) and residential wells (green) in the project area

C2-4 CONCEPTUAL MODEL

Initial Conceptual Model

A three dimensional, finite difference model code (MODFLOW) was initially selected to meet the number of modelling objectives. The selected code is widely accepted and includes a parameter estimation and optimization sub-routine (PEST) for calibration.

The initial model was conceptualized using drilling records and geologic data from a number of sources, including:

- Geologic mapping/model,
- Exploration drilling and testing, and
- Residential well logs from MOE's WELLS database

The conceptual model includes delineation of hydrostratigraphy, hydrogeologic properties of those strata, relationships between groundwater and surface water features, regional hydrologic (climatic) conditions, the mine development and closure plan, and an understanding of potential receiving environments (Figure 3).

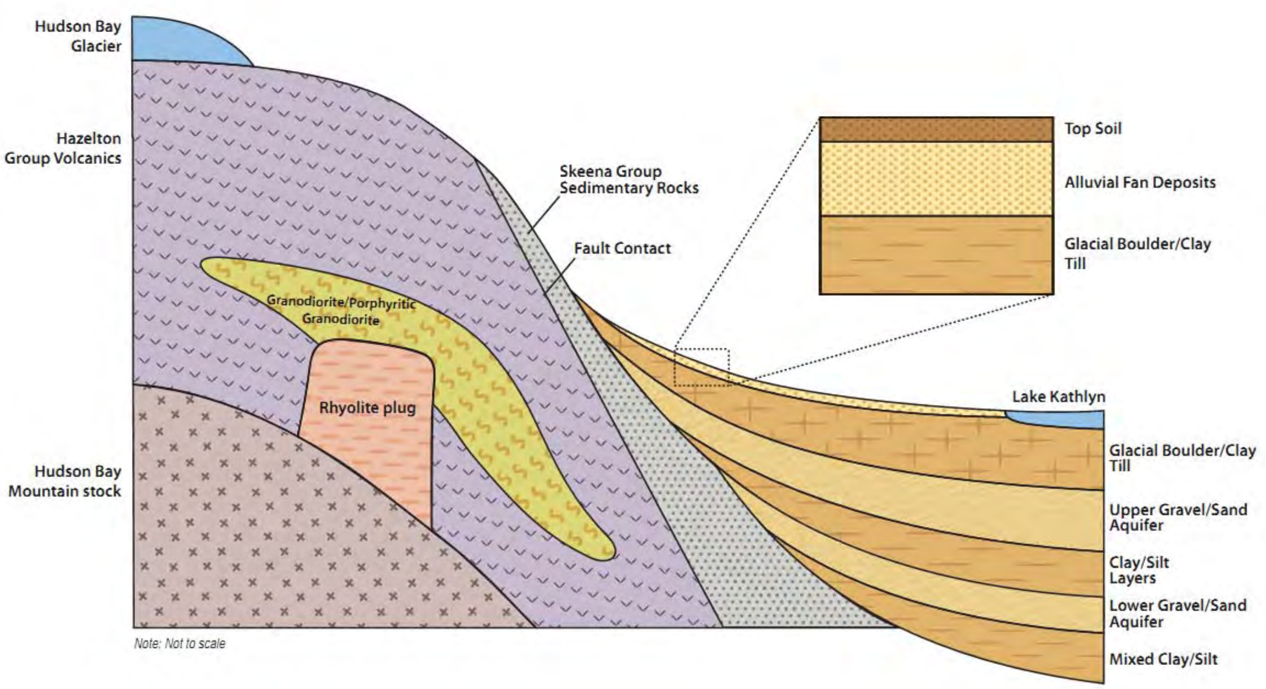


Figure 3: Conceptual model used for MODFLOW modelling

The sequence of modelling included several key steps, namely:

- baseline calibration to static water levels and seep estimates from the historic adit
- steady state simulation of mine operations
- transient simulation of post-closure conditions

Updates to the Conceptual Model

For the updated numerical model, MODFLOW was selected by the proponent as the most appropriate code for the modelling objectives. Furthermore, it was agreed that the code was commonly applied in practice and could be easily reviewed, hence lending to transparency during the decision making process. Although continuum models, like MODFLOW, do not address discrete bedrock fractures, the modeller notes that the applicability of an equivalent porous media approach to simulations of flow and transport in heterogeneous, fractured bedrock settings has been well proven and documented in other studies elsewhere. However the justification did not appear to be based on assessments of the conditions of the bedrock units at the site. The assumption of equivalent porous medium became a significant point of uncertainty from the perspective of the government reviewers.

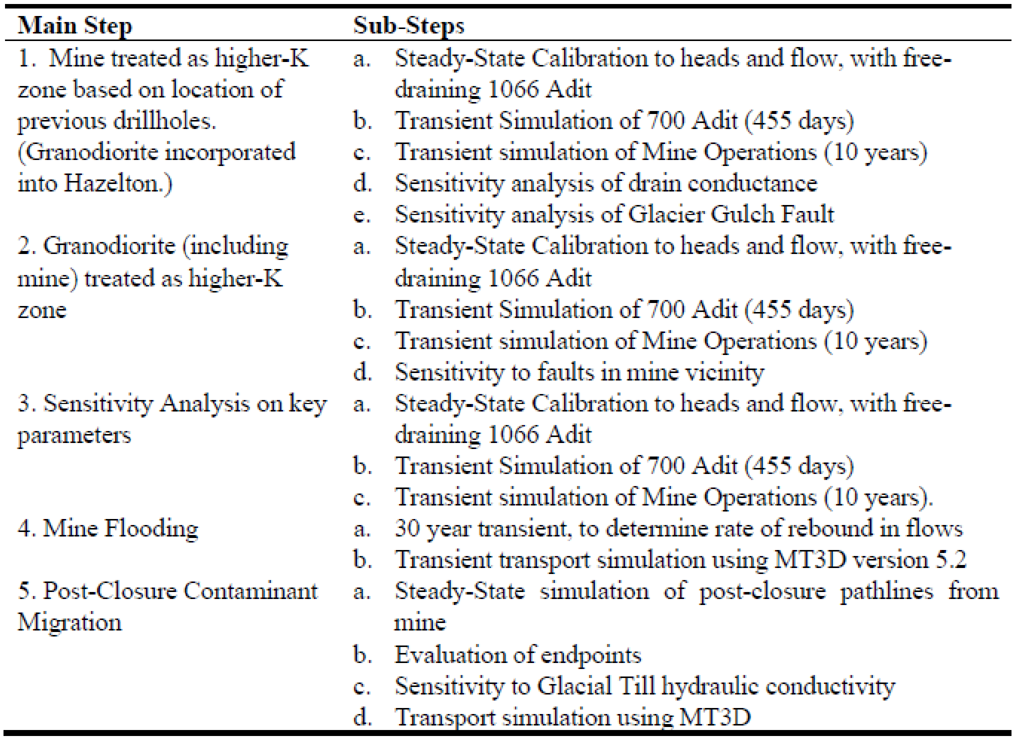
The original MODFLOW model was updated in several important areas. First, the model domain was both expanded to account for flow to adjacent watersheds, and simplified with respect to simulation of the complex underground workings. Second, a more thorough sensitivity analysis was conducted to assign ranges of key parameters to the model. Finally, transient simulations were used to revise estimates of previous steady state simulations during mine operations. Transient simulations were also used to predict flow and transport under different closure scenarios. These updates significantly improved the model.

The sequence of simulations for the updated model comprised the following steps:

- steady state calibration to heads and flow
- transient simulation of adit construction
- transient simulation of mine operation
- transient simulation of post-closure rebound, flow, and transport

The modelling approach used for the updated model is outlined in Table 1.

Table 1: Modelling approach for updated model



Main Step	Sub-Steps
1. Mine treated as higher-K zone based on location of previous drillholes. (Granodiorite incorporated into Hazelton.)	a. Steady-State Calibration to heads and flow, with free-draining 1066 Adit
	b. Transient Simulation of 700 Adit (455 days)
	c. Transient simulation of Mine Operations (10 years)
	d. Sensitivity analysis of drain conductance
	e. Sensitivity analysis of Glacier Gulch Fault
2. Granodiorite (including mine) treated as higher-K zone	a. Steady-State Calibration to heads and flow, with free-draining 1066 Adit
	b. Transient Simulation of 700 Adit (455 days)
	c. Transient simulation of Mine Operations (10 years)
	d. Sensitivity to faults in mine vicinity
3. Sensitivity Analysis on key parameters	a. Steady-State Calibration to heads and flow, with free-draining 1066 Adit
	b. Transient Simulation of 700 Adit (455 days)
	c. Transient simulation of Mine Operations (10 years).
4. Mine Flooding	a. 30 year transient, to determine rate of rebound in flows
	b. Transient transport simulation using MT3D version 5.2
5. Post-Closure Contaminant Migration	a. Steady-State simulation of post-closure pathlines from mine
	b. Evaluation of endpoints
	c. Sensitivity to Glacial Till hydraulic conductivity
	d. Transport simulation using MT3D

Modelling progressed from steady state calibration, to transient simulations of mine development, operation, and closure. To account for uncertainty in the conceptual model (in this case, the delineation of higher-K fractured bedrock), two distinct conceptual models were calibrated and used for model predictions. For both conceptual models, sensitivity analyses were performed on key parameters, namely:

- Drain conductance
- Fault location(s) and conductivity
- Hydraulic conductivity of key strata

During the sensitivity analyses, the parameters were adjusted within their reasonable limit, or until the calibration targets were not satisfied.

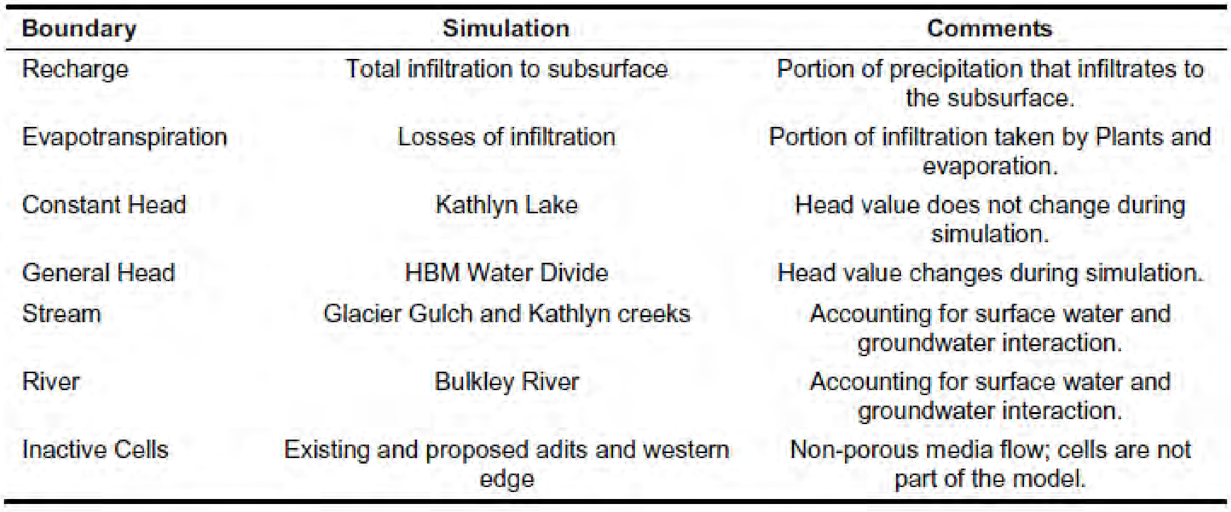
Pathline analysis and a solute transport simulation were carried out to assess the post-closure impacts of mine-affected groundwater on the receiving environments.

C2-5 NUMERICAL MODEL SETUP

Initial Model Setup

For the initial model setup, the Site was discretized into 45 rows, 130 columns, and 40 layers. Grid spacing was refined near the underground workings and adits. The model grid was bounded by a major river to the east, a topographic divide (Coast Mountains) to the west, and to the north and south to include potentially sensitive creeks. Boundaries to the north and south were assigned no flow boundaries, while the Coast Mountains to the west were treated as a general head boundary. The river to the east was represented with a river boundary with elevation and discharge values determined from field investigations. Stream boundaries were assigned to the two streams of interest. A constant head boundary was assigned to the lake representing its measured elevation. Recharge was applied to the model domain with values representing the balance of precipitation, runoff, evapotranspiration, contributions from up-gradient sources (faults or fractures), and sub-glacial seepage where appropriate. Table 2 provides a summary of these assigned boundary conditions and Figure 4 provides a visual representation of the model boundaries for the initial model.

Table 2: Summary of assigned boundary conditions



Boundary	Simulation	Comments
Recharge	Total infiltration to subsurface	Portion of precipitation that infiltrates to the subsurface.
Evapotranspiration	Losses of infiltration	Portion of infiltration taken by Plants and evaporation.
Constant Head	Kathlyn Lake	Head value does not change during simulation.
General Head	HBM Water Divide	Head value changes during simulation.
Stream	Glacier Gulch and Kathlyn creeks	Accounting for surface water and groundwater interaction.
River	Bulkley River	Accounting for surface water and groundwater interaction.
Inactive Cells	Existing and proposed adits and western edge	Non-porous media flow; cells are not part of the model.

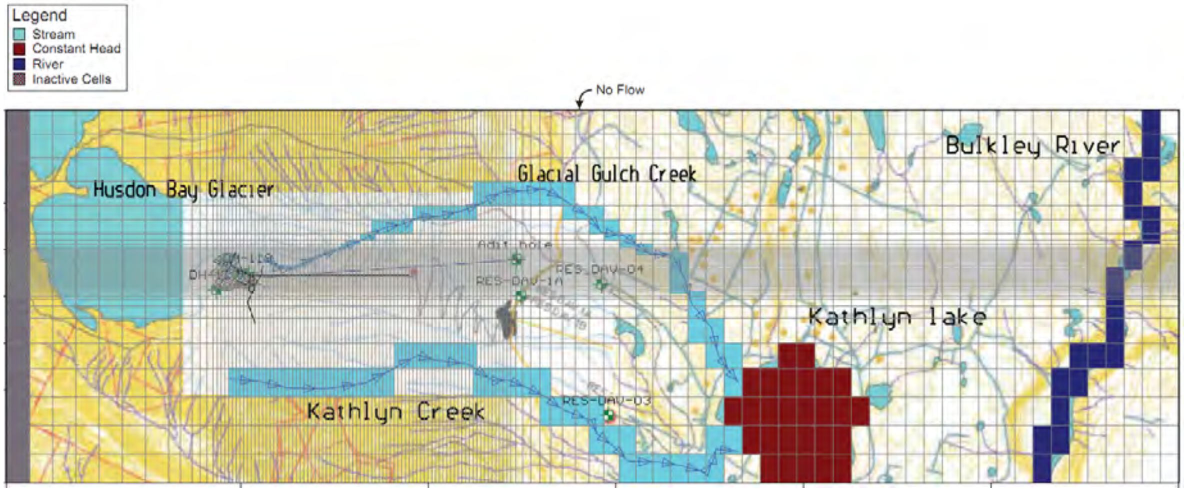


Figure 4: Boundary conditions and model discretization for the initial model

To simulate the discharge to the underground mine, inactive cells (representing the workings) were surrounded by drain cells. The drain cells simulated bedrock seepage faces. Drains on the sides of the workings (representing vertical faces) were assigned heads at the middle of the cell, while drains above and below the workings were assigned head values at the top of the cells. Figures 5 and 6 illustrate the drain set-up.

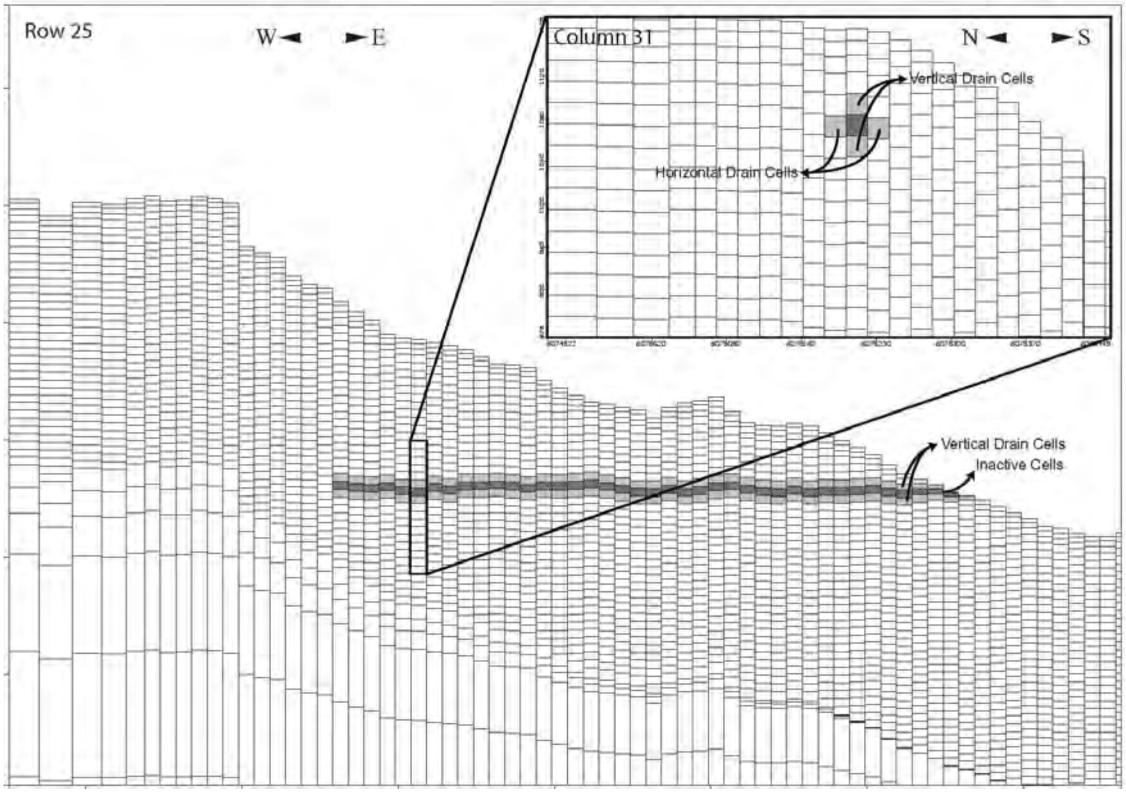


Figure 5: Drain and inactive cell set-up for representing mine workings

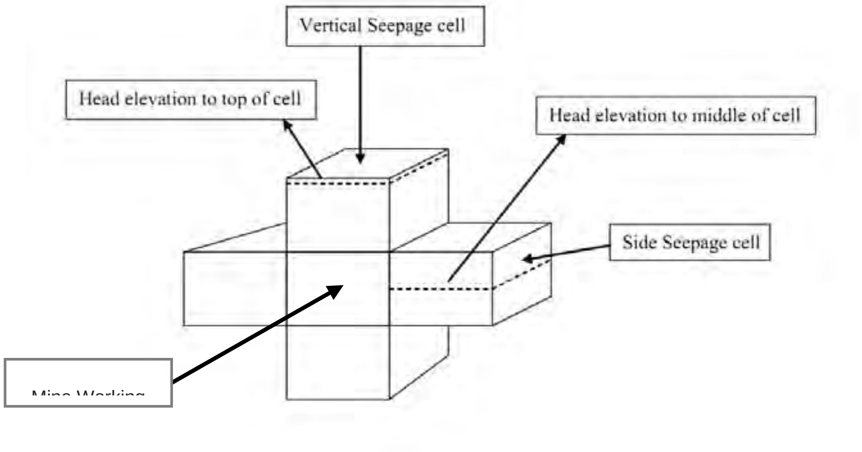


Figure 6: Mine working and drain set-up for initial model

Updated Model Setup

In the updated model, the domain was expanded to the north and south to allow for interactions between the adjacent watersheds and the mine. The updated model domain and boundary conditions are illustrated in Figure 7. Fourteen surface water features were included as constant head and general head boundary conditions (lakes and marshes, respectively).

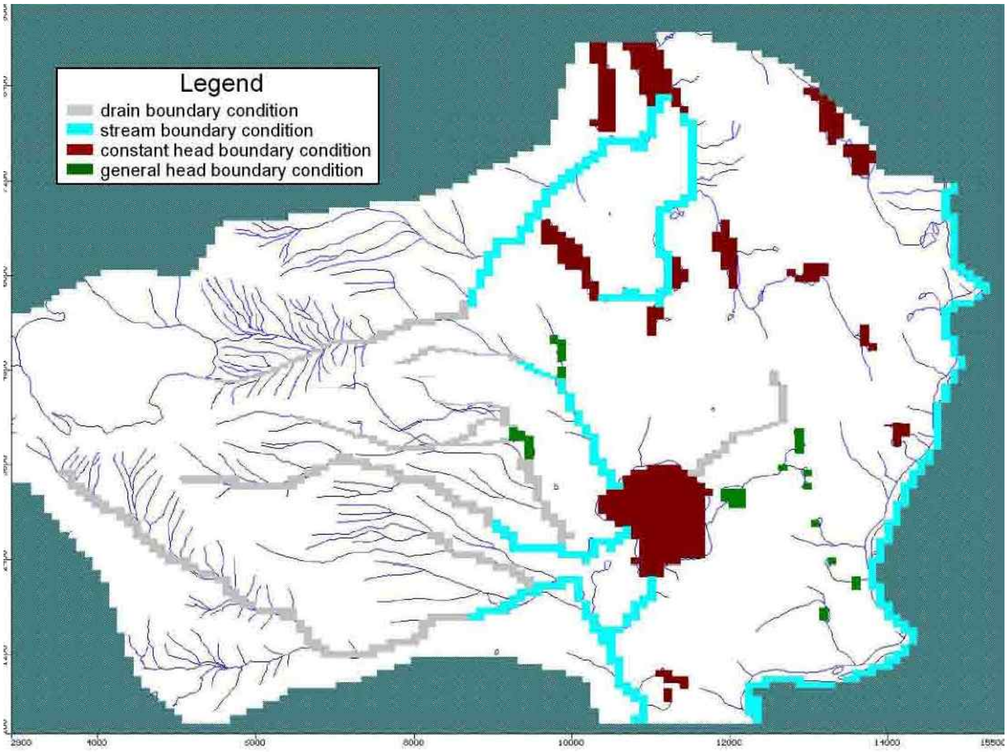


Figure 7: Model domain and boundary conditions for updated model

The vertical discretization was reduced from 40 layers to 17 layers without compromising the delineation of hydrostratigraphic zones. To represent the underground mine workings, simple drains replaced the more complicated inactive zone-drain combination used in the updated model (Figure 8).

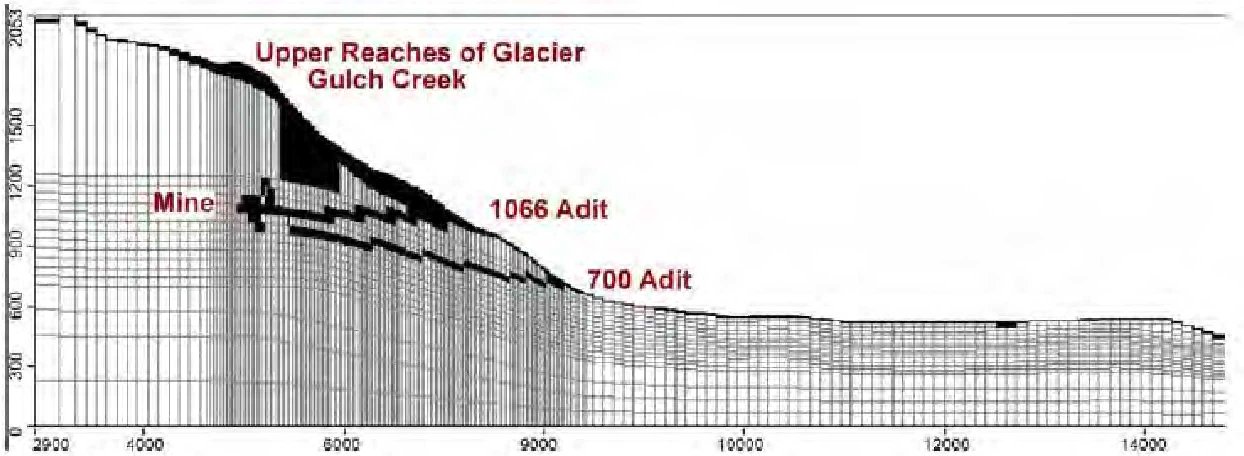


Figure 8: Updated model with simplified expression of mine workings as drains

Recharge was applied to four distinct regions of the model domain to represent the various hydrologic regimes present (Figure 9).

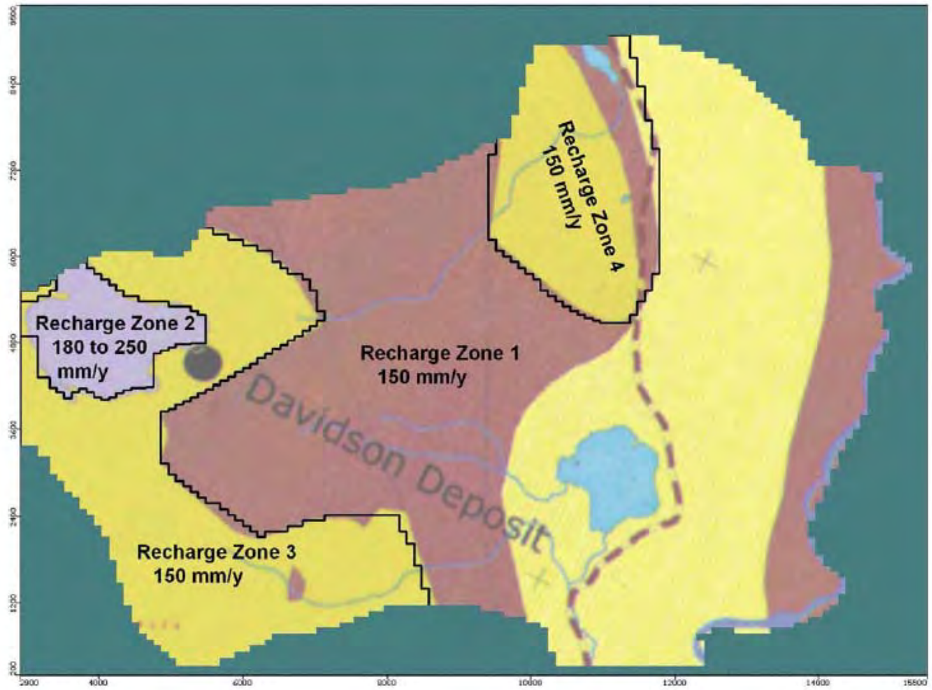


Figure 9: Recharge zones for updated model

C2-6 MODEL CALIBRATION

Initial Model Calibration

The model was initially run with steady state conditions for 40 years to calibrate the simulated historic adit discharge to the observed adit discharge. This time period represents the age of the historic adit.

Water level calibration data are notably limited in this study. The steady state flow model was calibrated to water levels in just five boreholes and a water level from a hole in the floor of the adit. The Parameter Estimation and Optimization (PEST) sub-routine for MODFLOW was used to meet calibration targets within the 95% confidence interval (Figure 10).

The calculated root mean square (RMS) error was approximately 5% and was judged by the modeller to be acceptable for this simulation.

Packer testing showed significant variability in estimated bedrock hydraulic conductivity, hence multiple cases were simulated in the initial round of modelling. Both isotropic and anisotropic conditions (vertical only; hydraulic conductivities of the bedrock units were assumed to be isotropic in the X-Y plane) were applied to three variations of hydraulic conductivity distributions, for a total of six model scenarios. This approach provided a range of discharge estimates corresponding to the uncertainty in the magnitudes and spatial distribution of hydraulic conductivity within the conceptual model. From the simplistic isotropic models, the scenario with the tightest distribution of conductivity that excluded apparent outlier values was considered most reasonable. From the more realistic anisotropic cases, it was determined that the most probable estimate of bedrock hydraulic conductivity (based on the resultant discharge values) lies between ½ order of magnitude above the geometric mean to 1 order of magnitude below the geometric mean of the packer test estimates. From this rationale, a plausible upper bound and lower bound on bedrock conductivity was proposed with a corresponding range of plausible discharge values.

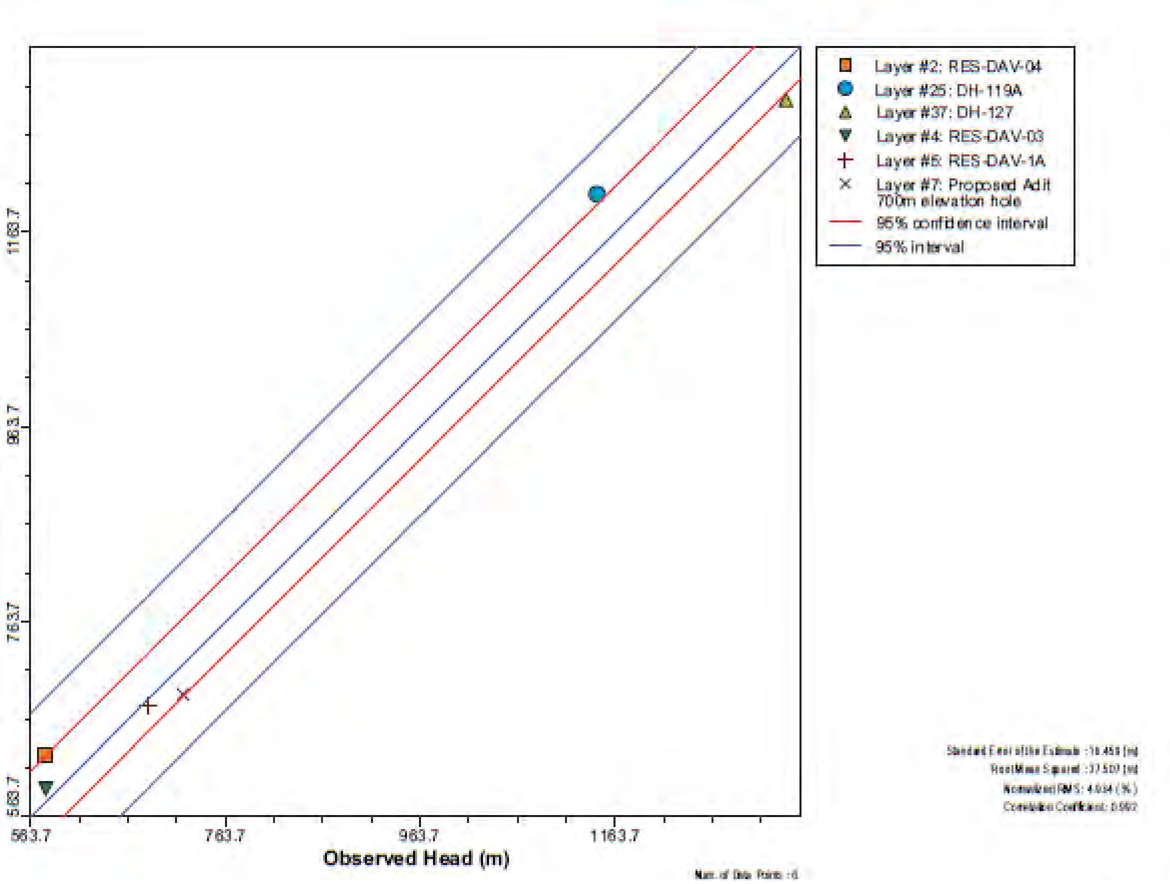


Figure 10: Observed vs. simulated water levels after model calibration

Updated Model Calibration

The calibration was carried out in two distinct phases of parallel modelling. Due to uncertainty in the conceptual model, two simulations (Model A and Model B) were carried through the steady state head and flow calibration phases. Both models are based on the hydrogeologic units presented in Figure 11. These simulations did not initially include the major fault zone inferred to run through the Site.

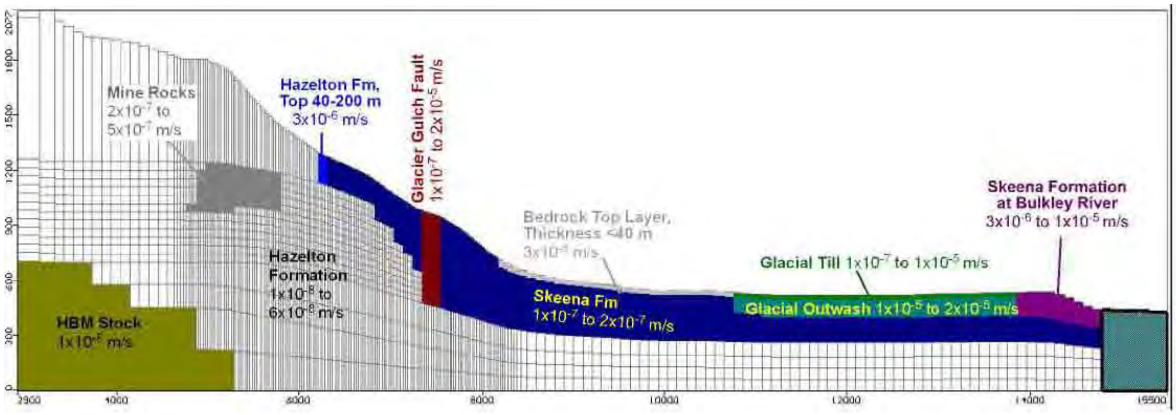
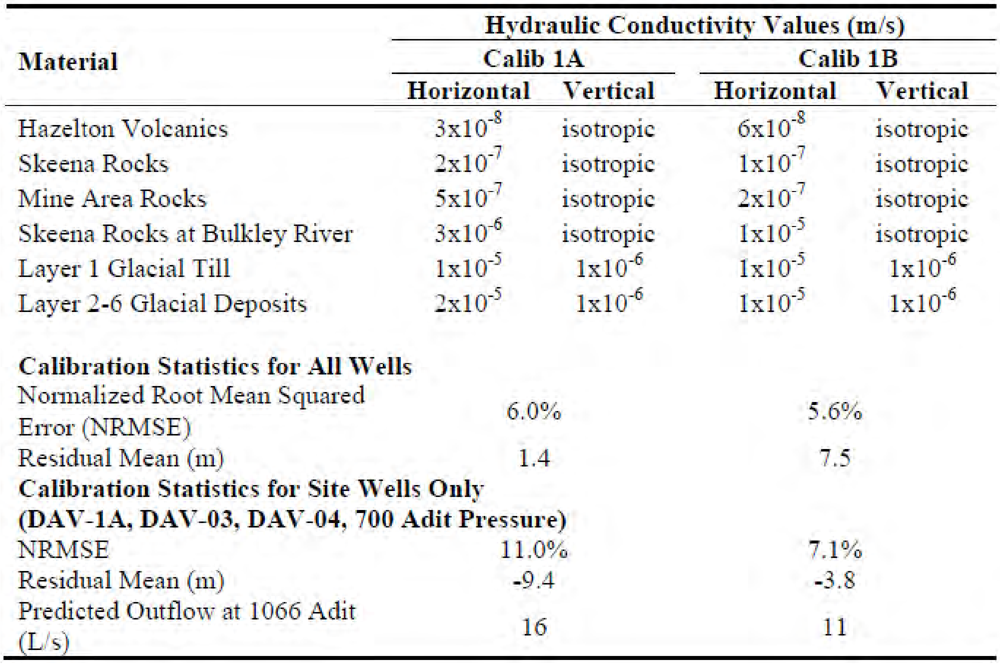


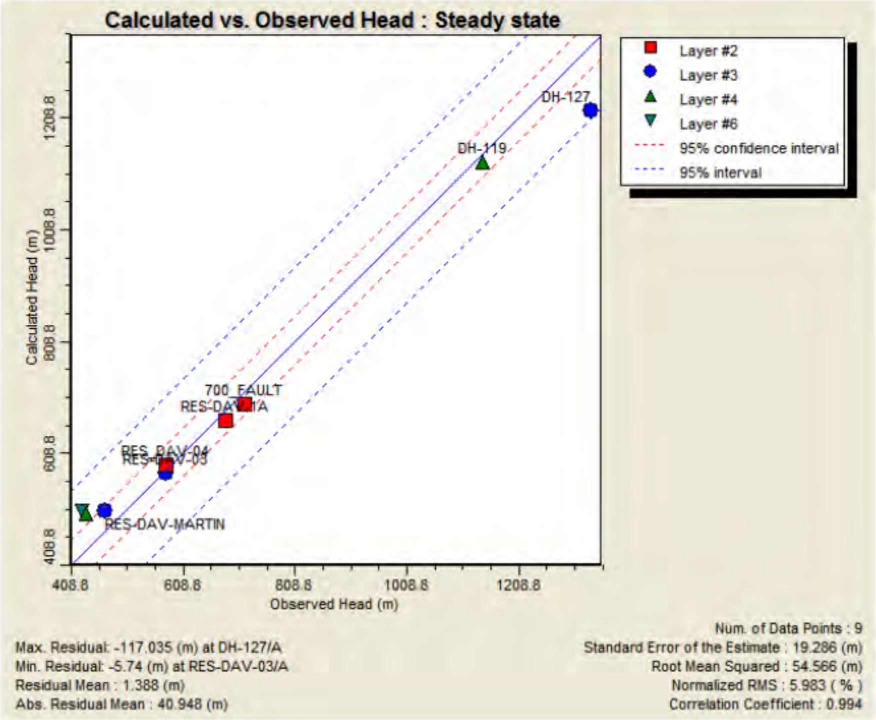
Figure 11: Distribution of hydrogeologic units for First Calibration

Head and flow values available for calibration of the steady state model were very limited. The model was calibrated to head measurements in eight wells, one fracture zone in the area of the new adit, and long-term, steady flows from the historic adit. The hydraulic conductivity values of the various rock formations were adjusted within a reasonable range to calibrate the simulated adit seepage to the actual observed outflow (“1066 Adit”). Table 3, Figure 12, and Figure 13 present the results of this first round of calibration.

Table 3: Results of First Calibration runs



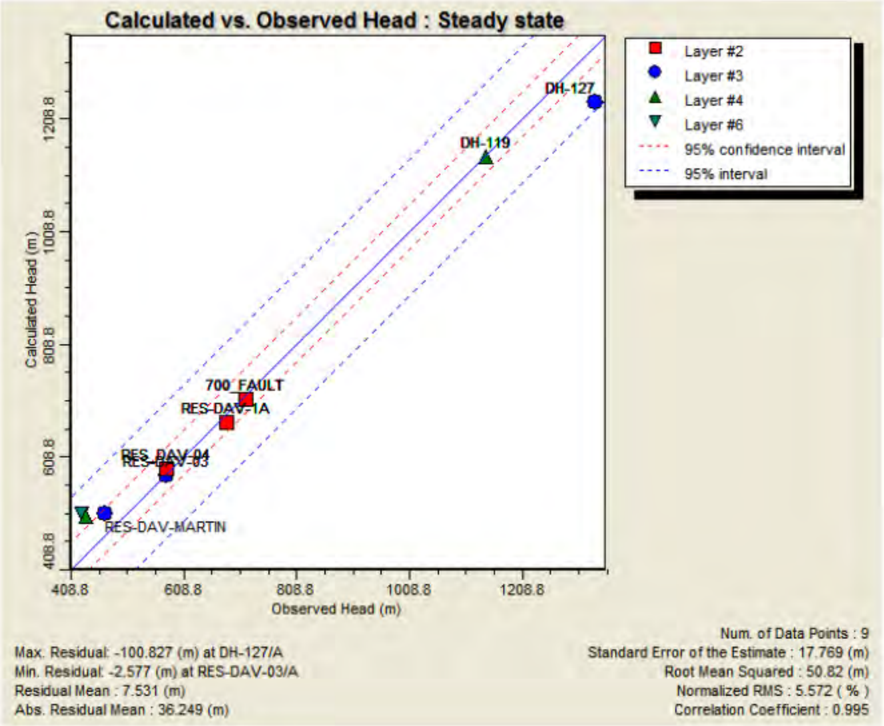
Material	**Hydraulic Conductivity Values (m/s)**			
	Calib 1A		**Calib 1B**	
	Horizontal	**Vertical**	**Horizontal**	**Vertical**
Hazelton Volcanics	$3x10^{-8}$	isotropic	$6x10^{-8}$	isotropic
Skeena Rocks	$2x10^{-7}$	isotropic	$1x10^{-7}$	isotropic
Mine Area Rocks	$5x10^{-7}$	isotropic	$2x10^{-7}$	isotropic
Skeena Rocks at Bulkley River	$3x10^{-6}$	isotropic	$1x10^{-5}$	isotropic
Layer 1 Glacial Till	$1x10^{-5}$	$1x10^{-6}$	$1x10^{-5}$	$1x10^{-6}$
Layer 2-6 Glacial Deposits	$2x10^{-5}$	$1x10^{-6}$	$1x10^{-5}$	$1x10^{-6}$
Calibration Statistics for All Wells				
Normalized Root Mean Squared Error (NRMSE)	6.0%		5.6%	
Residual Mean (m)	1.4		7.5	
Calibration Statistics for Site Wells Only (DAV-1A, DAV-03, DAV-04, 700 Adit Pressure)				
NRMSE	11.0%		7.1%	
Residual Mean (m)	-9.4		-3.8	
Predicted Outflow at 1066 Adit (L/s)	16		11	



Max. Residual: -117.035 (m) at DH-127/A
Min. Residual: -5.74 (m) at RES-DAV-03/A
Residual Mean : 1.388 (m)
Abs. Residual Mean : 40.948 (m)

Num. of Data Points : 9
Standard Error of the Estimate : 19.286 (m)
Root Mean Squared : 54.566 (m)
Normalized RMS : 5.983 (%)
Correlation Coefficient : 0.994

Figure 12: Results of First Calibration (Model A)



Max. Residual: -100.827 (m) at DH-127/A
Min. Residual: -2.577 (m) at RES-DAV-03/A
Residual Mean : 7.531 (m)
Abs. Residual Mean : 36.249 (m)

Num. of Data Points : 9
Standard Error of the Estimate : 17.769 (m)
Root Mean Squared : 50.82 (m)
Normalized RMS : 5.572 (%)
Correlation Coefficient : 0.995

Figure 13: Results of First Calibration (Model B)

Calibration results for Model A and Model B show normalized root mean square error (NRMSE) of less than 10%, which the modeller judged as acceptable given the size of the dataset.

C2-7 MODEL PREDICTIONS & SENSITIVITY ANALYSES

Initial Model Predictions

The initial model was run at steady state for 40 years to calibrate adit discharge and subsequently for 10 years to simulate the life of the project. The groundwater flow field for the Site is presented Figure 14. Following operations, the model was run transiently for one thousand years to simulate post-closure conditions.

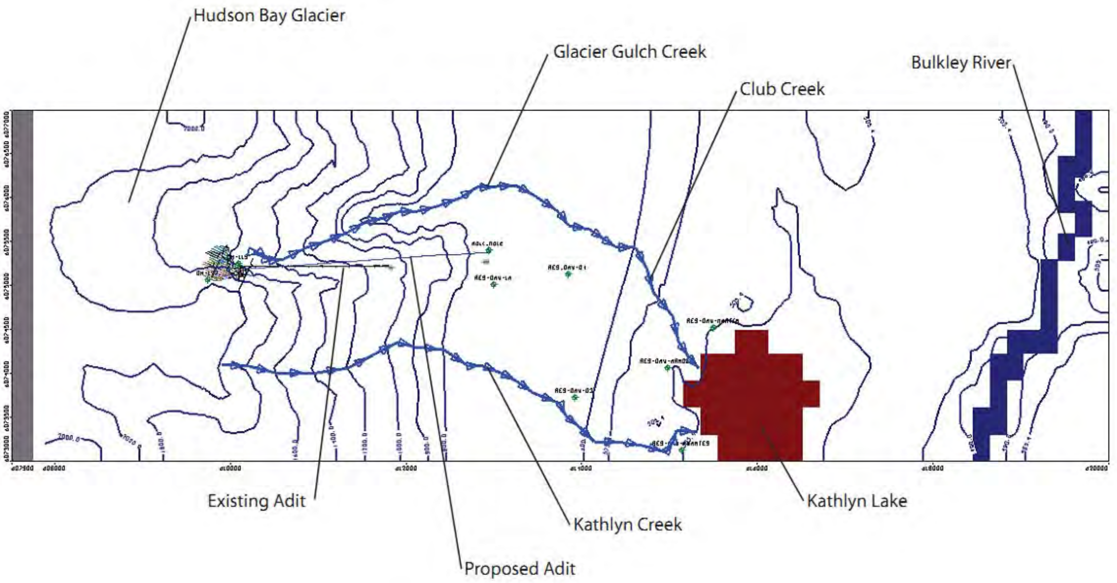


Figure 14: Groundwater equipotentials and flow directions

The steady state runs were used to estimate a range for discharge to the mine workings (Figure 15) and to generate travel time estimates (based on assumed porosities) for mine-related particles travelling to downstream receptors.

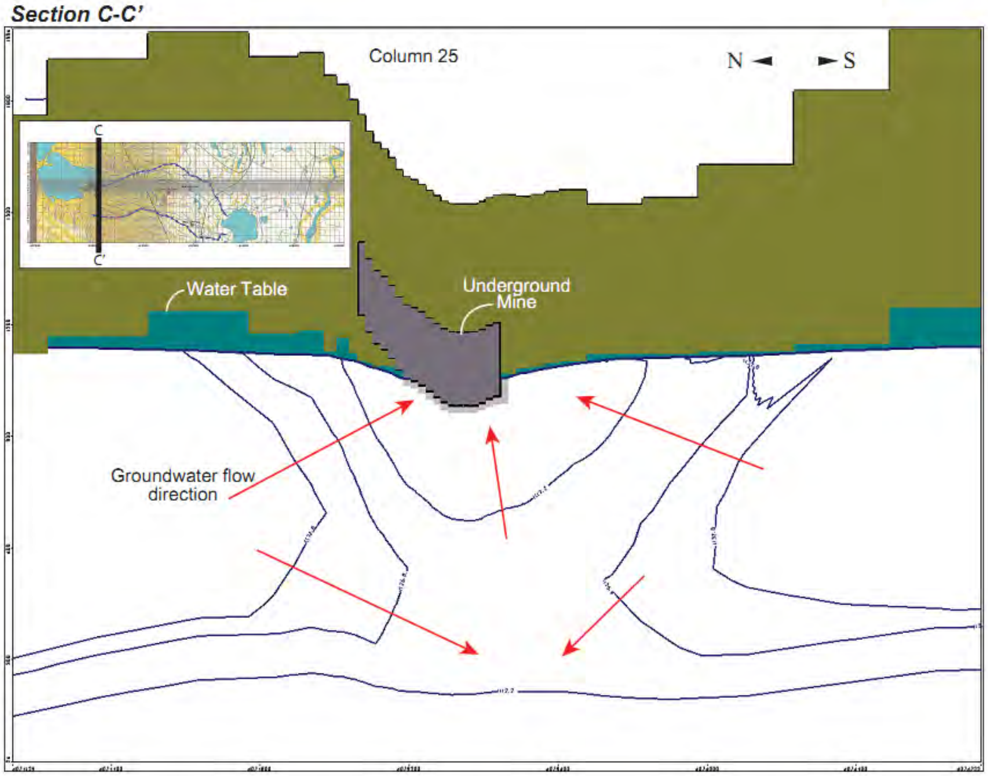


Figure 15: Groundwater flow to mine workings

The transient runs were used to assess the infilling rate of mine workings after closure and the change in flow field as a result of mine flooding. Transport modelling runs were also built off the transient simulations.

Updated Model Predictions

The calibration models derived from the steady state calibration were used as initial conditions for the transient simulations of mine development, operation, and closure.

The two models, slightly different in concept, were used to provide a range of estimates of discharge over the mine life (Figure 16).

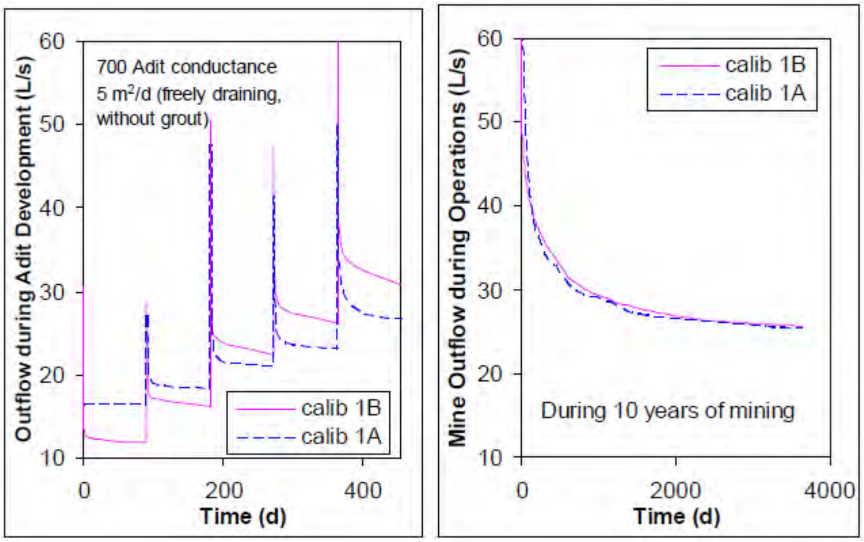


Figure 16: Discharge estimates for adit construction and mine operation.

As Model B provided higher estimates of discharge (more conservative), it was selected for a sensitivity analysis of drain conductance. Drain conductance in this model represents, in effect, the efficacy of grouting employed to prevent seepage into the underground workings. This is effectively an operational parameter that may be adjusted during construction. A higher drain conductance in the simulation represents a less effective grout, while a low conductance would represent a grout that precludes seepage into the workings. Figure 17 presents the results of this sensitivity analysis.

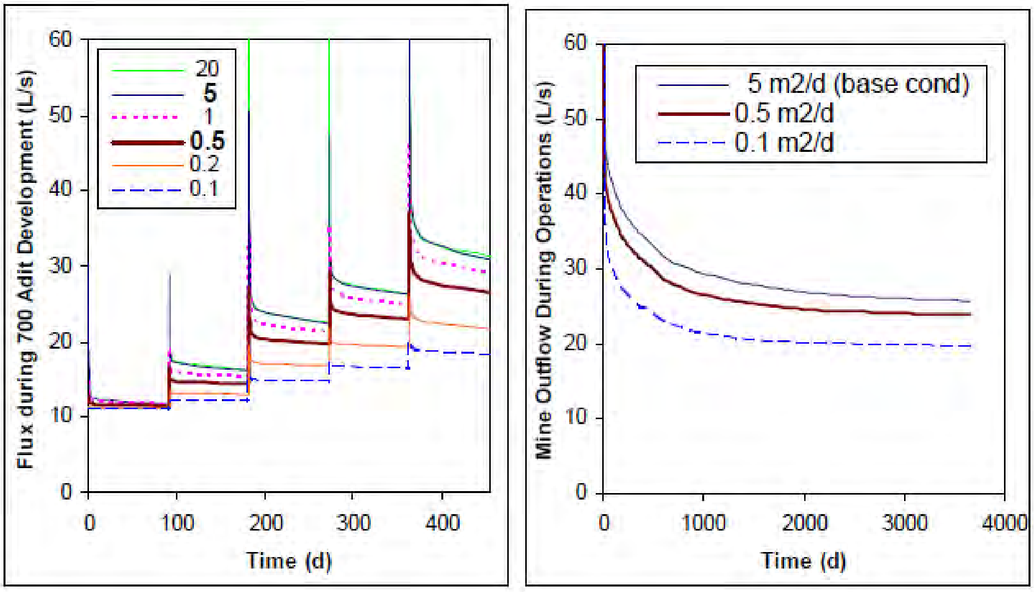


Figure 17: Sensitivity analysis of simulated drain conductance

Further sensitivity analysis was performed with respect to the inclusion of a prominent fault structure through the Site. Inclusion of the fault zone in the model only slightly reduced discharge to the mine workings by effectively lowering the water table in the mine area. The only scenario that would result in increased discharge to the mine is a highly transmissive fault that effectively connects the underground workings to the area of sub-glacial recharge west of the mine; however, this scenario was simulated to increased discharge only slightly.

In addition to Model A and Model B of the First Calibration stage, a Second Calibration phase involved the inclusion of a new hydrogeologic unit in the mine area to represent a zone of (relatively) higher hydraulic conductivity. The distribution of hydrogeologic units of this third model is presented in Figure 18. Furthermore, the rate of sub-glacial recharge was increased in order to assess model sensitivity to this parameter.

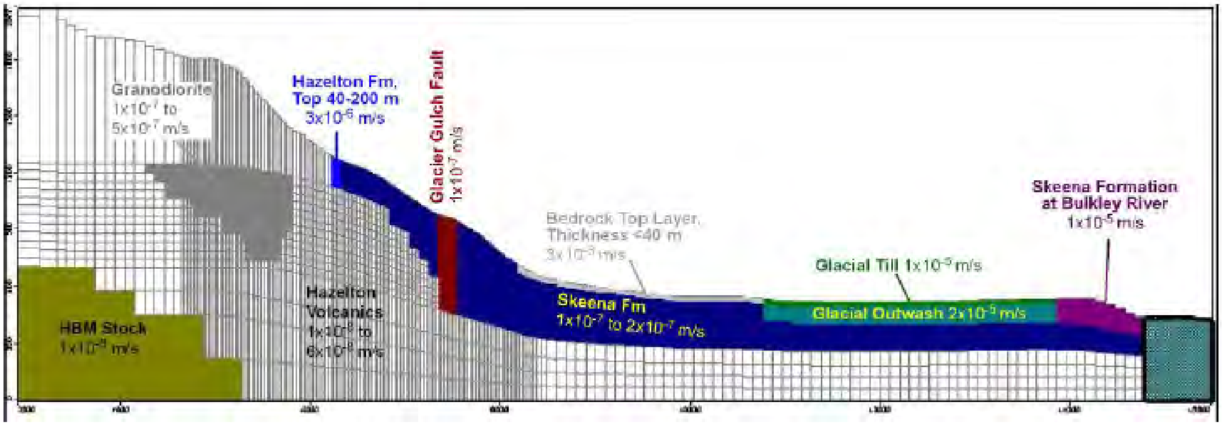


Figure 18: Model from Second Calibration phase with new hydrogeologic unit in the mine area

Again, the calibration targets were achieved for this conceptual model and are presented in Figure 19.

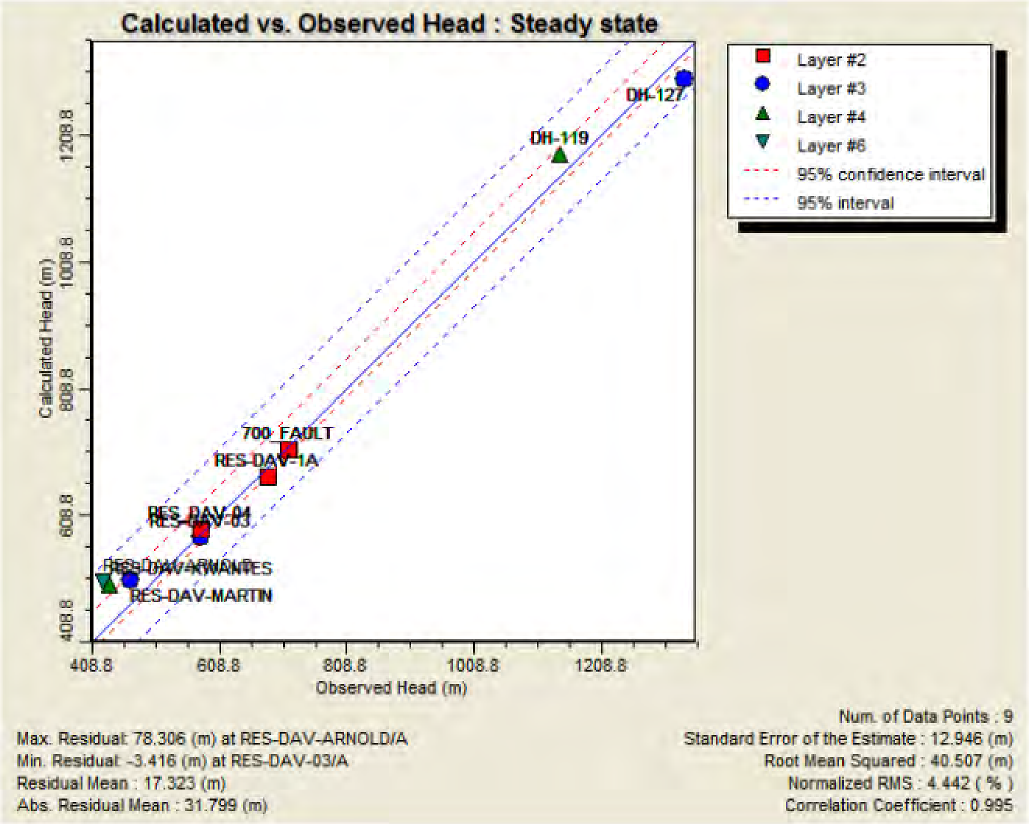


Figure 19: Calibration results for Second Calibration model

The third model predicts higher discharge values compared to the models of the First Calibration. These results are compared in Table 4.

Table 4: Comparison of simulated discharge

Discharge Zone	Calib 1A	Calib 1B	Calib 2
Peak Modeled 700 Adit Flow[1]	35	29	42
Flow at end of Adit Development	25	27	29
Mine Flow 5-d into Mine Operation[2]	51	43	47
End of Mine Life Flow	21	22	26

Further sensitivity analyses were undertaken to observe the effect of hydraulic conductivity perturbations on the solutions from the Second Calibration. The hydraulic conductivity values assigned to each hydrogeologic unit were systematically varied to assess which have the greatest impact on mine discharge values. Through this process, it was determined that the model was most sensitive to the rock unit that hosts the mine workings.

Additionally, the model sensitivity to recharge was studied. Sub-glacial recharge west of the mine was shown to dramatically influence discharge estimates.

From the combination of models and sensitivity runs, an upper bound estimate of mine discharge was estimated. This estimate represents the worst-case (most reasonably conservative) scenario under the range of simulated conditions.

Further estimates of streamflows were provided, all of which are similar across the three main model runs.

C2-8 TRANSPORT MODELLING

Initial Model Transport Simulations

During the initial round of numerical modelling, a particle tracking module (MODPATH) was used to estimate the advective path and travel time of a group of particles introduced to the system (Figure 20). Particles were assigned to the new adit, the underground stopes, and beneath the load-out facility. The time required for a particle to reach a common downstream receptor (given upper and lower bound conditions) was used to assess the risk to the receiving environment.

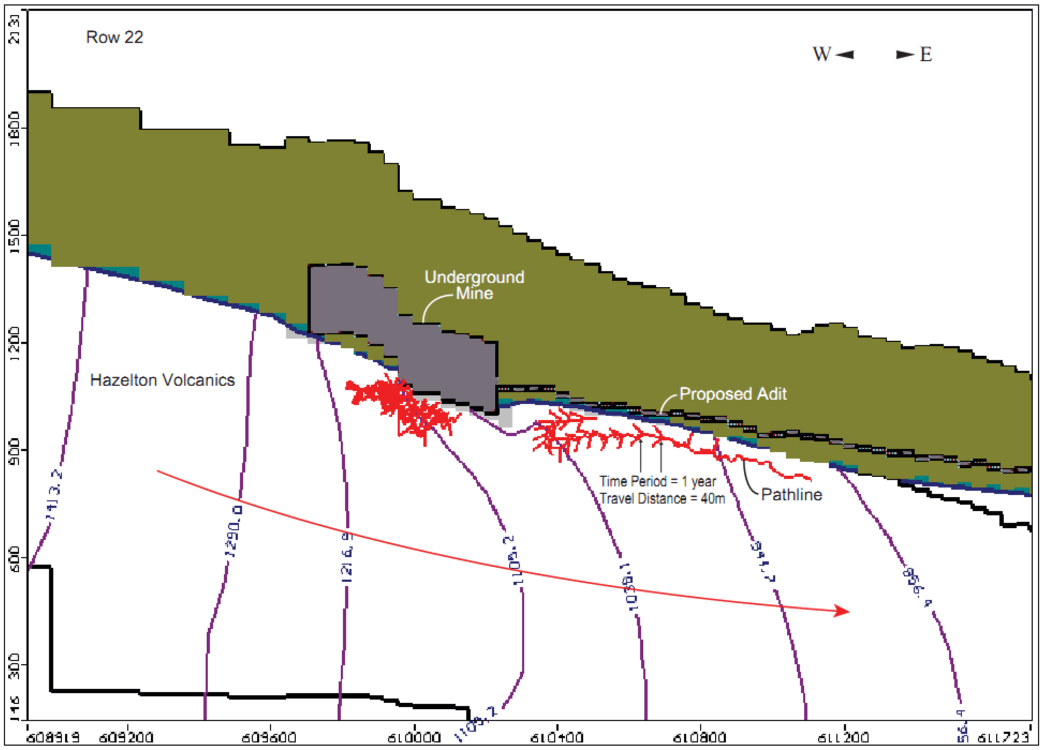


Figure 20: Pathline analysis using MODPATH

Following the MODPATH simulations, the solute transport module, MT3DMS, was used to simulate the transport of total organic carbon (TOC) to the receiving environment. A single value representing the initial TOC concentration was assumed based on a consultant's report. The transport simulation was conducted as two separate scenarios: (1) where TOC does not react or degrade with time, and (2) where TOC is reactive and decays with time.

Three observation wells were created in the model domain to track the break-through of TOC over time (Figure 21). These wells were located upstream of the sensitive receiving environments and distributed spatially (across the domain as well as with depth). The results are presented as break-through curves in Figure 22.

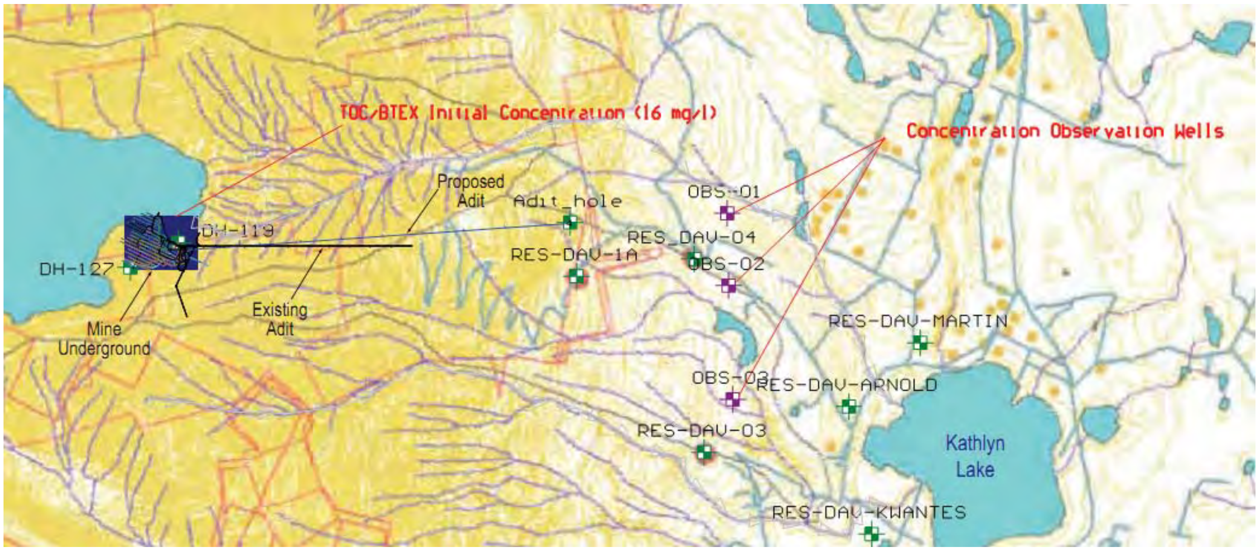


Figure 21: Location of simulated observation wells (purple) along with existing residential and monitoring wells (green)

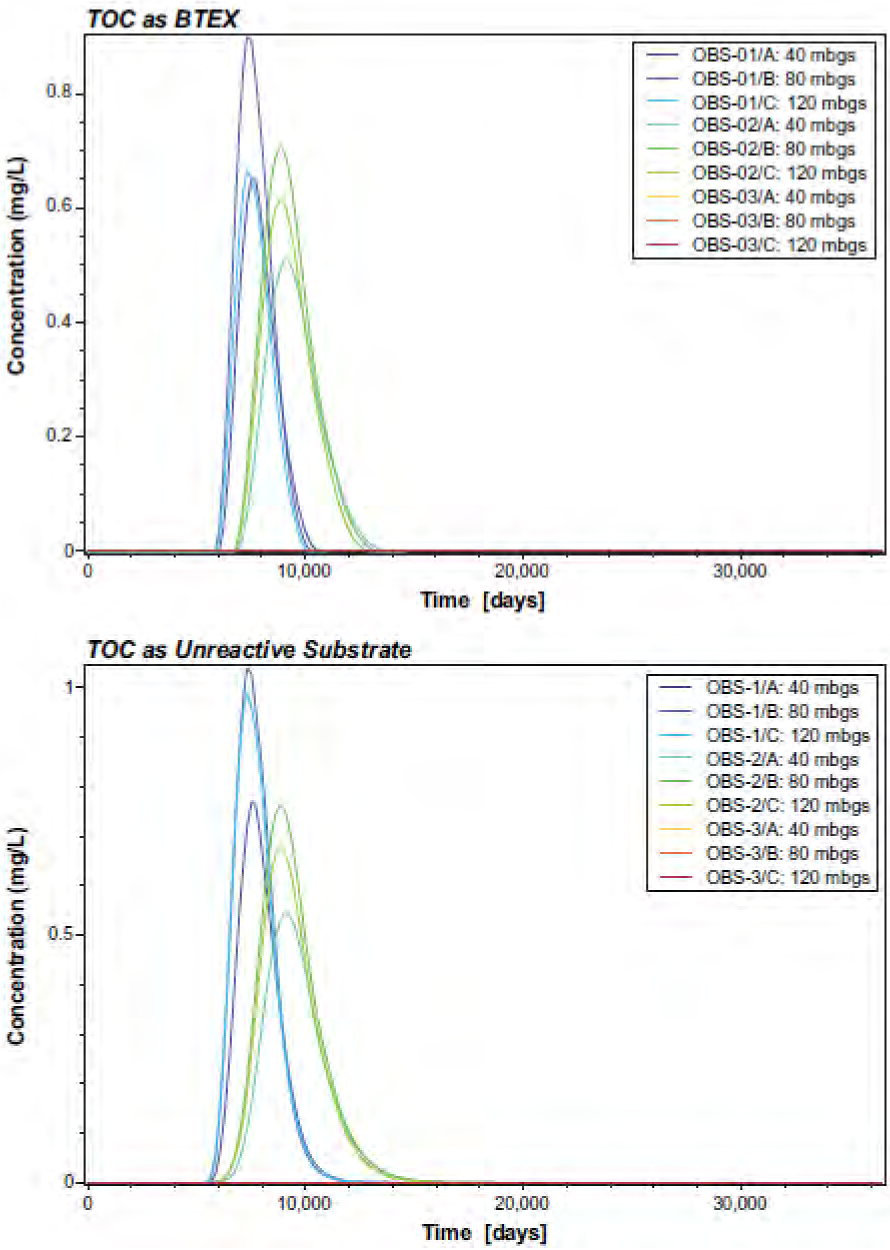


Figure 22: Break-through curves for TOC

Updated Model Transport Simulations

During operation, the mine will act as a sink and groundwater flow to receptors is unlikely to occur. However, after mine closure and rebound of the water table, mine-affected groundwater will migrate and may impact the downgradient environment. Particle tracking (MODPATH) confirmed that mine CoCs may reach groundwater discharge points several decades after closure. The particle tracking exercise helped to identify potential receptors, while not able to provide estimates of CoC concentration. At this point, an additional sensitivity analysis was performed to assess the effect of the shallow till hydraulic conductivity. The effect was to deflect particles towards different areas of the receiving environment (e.g.

away from a lake and towards a river) which could have significant implications regarding receptor sensitivity and dilution capacity.

An analysis of geochemical data from the historic adit provided evidence to support the enlargement of the hydrogeologic unit hosting the mine workings. This was performed as the Third Calibration phase and this final model – which still agreed with flow simulations from the First and Second Calibration models – was used for transport simulations.

The transport module MT3D was used to simulate non-reactive transport of a nonspecific mine CoC from the mine workings (representing 100% concentration). The default values for dispersivity were adopted. Simulations of post-closure transport indicate that supply wells and surface water will not receive a significant percentage of the solute in the 100 year timeframe simulated (Figures 23, 24, 25).

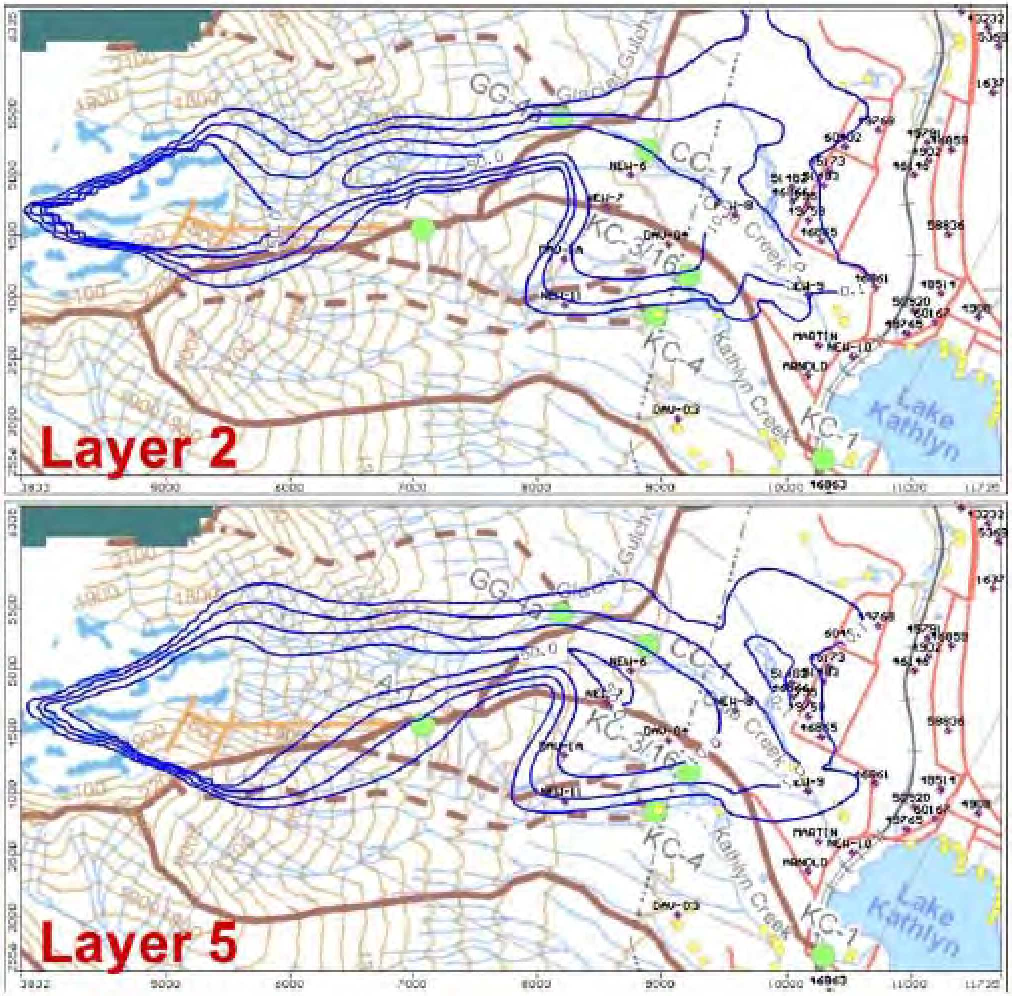


Figure 23: Predicted concentration contours (blue) at 100 years after mine closure for depths represented by Layers 2 and 5 of the model. Contours at 50, 10, 1, and 0.1% of mine concentration.

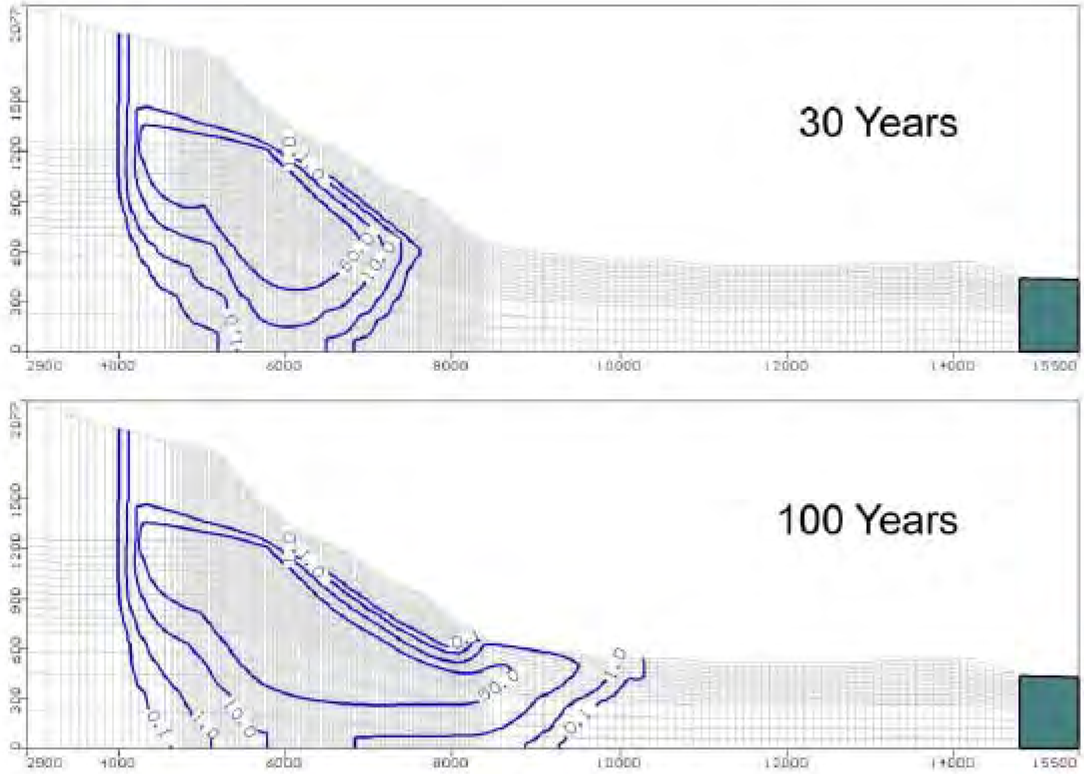


Figure 24: Vertical distribution of mine solute at 30 and 100 years after mine closure. Contours at 50, 10, 1, and 0.1% of mine concentration.

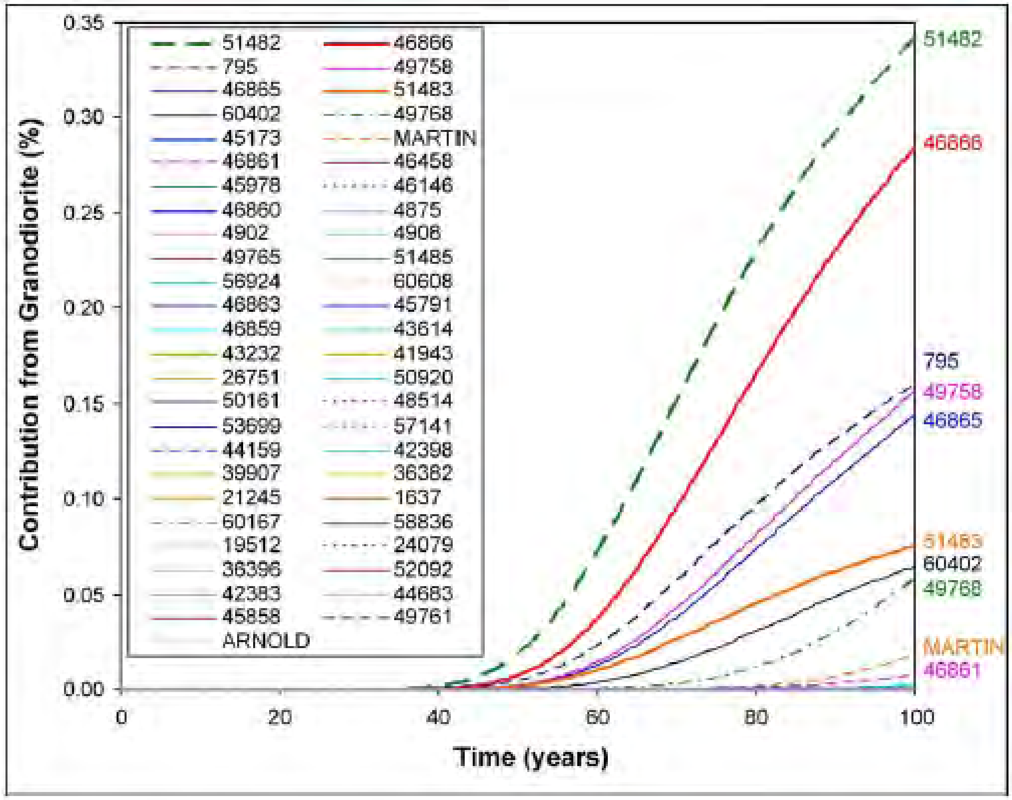


Figure 25: Mine-affected groundwater concentrations at local supply wells.

Additional analyses were performed with a subsequent model to show that the downstream supply wells would receive only 1% more groundwater from the mine area compared to pre-mining conditions.

On the basis of transport simulations and the predicted path of the mine-affected plume, additional groundwater monitoring well locations were recommended by the modeller.

C2-9 CASE STUDY EVALUATION

The initial numerical model was limited by scarce calibration data and a wide range of interpreted hydraulic parameters from hydraulic testing – this was deemed to be a significant point of uncertainty by government reviewers. A statistical approach was used to assess the plausible range of hydraulic conductivity values; however, in doing so the entire range of hydraulic testing results were not adopted (some values were deemed as outliers).

The updated model was limited by the same sparse dataset and uncertainty in the conceptual model. However, a thorough sensitivity analyses provided a more defensible range of flow and transport solutions to meet the modelling objectives. In this case, the modeller acknowledged that the accuracy of the model is limited by the quality and quantity of data and the timeframe over which it was collected. Furthermore, the modeller demonstrated that model calibration is non-unique in that more than one set of parameters may result in a solution that meets calibration targets. The aspect of non-uniqueness was addressed quite thoroughly during this modelling exercise.

In both modelling phases, prior field investigations were acknowledged and data was incorporated into the conceptualization and calibration procedures. This data was, however, limited spatially and temporally.

The conceptualization of the hydrostratigraphy and groundwater flow is well presented and, in the case of the updated model, the modeller has made an attempt to capture the conceptual uncertainty in two baseline models.

The modelling code was selected for its transparency and for ease of review. Furthermore, the updated model was constructed in the likeness of the former simulations which allowed for some continuity and comparison between models. A 3D numerical model was essential for simulating the complex groundwater flow and discharge associated with the underground mine workings and spatial distribution of hydrogeologic units. The level of risk associated with the valued ecosystem components merited a detailed numerical model on which solute transport simulation could be based.

Transport simulations were conducted during both phases of modelling. Simulations included simple steady state pathline analyses as well as transient transport simulations of both reactive and non-reactive species. The updated model provided a sensitivity analysis regarding the permeability of aquifer units nearest the environmental receptors and a thoughtful analysis of the impact of mine-affected groundwater on supply wells in the downstream environment. A thorough analysis of geochemical data was also undertaken in the second modelling attempt which led to refinement of the conceptual model.

Calibration targets were met with the aid of an automated calibration sub-routine in the first instance; however, this process was not fully and transparently explained in the model documentation reviewed for this case study. Furthermore, the model sensitivity to boundary conditions and the impact of preferential pathways was not presented clearly in the model documentation as reviewed. During calibration of the updated model, multiple conceptual models were calibrated to head and flow measurements. This calibration process was revisited throughout the modelling process to ensure that the model was calibrated with the project-specific objectives in mind. In all instances of modelling, the dataset available for calibration was extremely limited given the complexity of the site and the sensitivity of the receiving environment. This limited dataset should not be considered exemplary.

Sensitivity analyses were undertaken at nearly every stage of modelling. Sensitivity of the model to operational parameters (grouting), preferential flow paths (faults), and boundary conditions (e.g. sub-glacial recharge) was examined and incorporated into upper bound flow and transport estimates.

Predictions of solute transport carry a significant uncertainty because site-specific transport parameters were not available and the transport model could not be calibrated. The limitations in applying a solute transport model to this complex bedrock environment are not discussed in the modelling report.

The updated groundwater flow and solute transport models were applied to meet the modelling objectives and to provide plausible upper bound estimates on the impact of mine operations in this environment. However, the results are prefaced by the extremely limited dataset on which model conceptualization and calibration were based.

In summary, there were several major points of uncertainty related to the numerical model. Primarily, data was limited for calibrating the model. As well, major assumptions of equivalent porous medium for fractured bedrock, horizontal isotropy of hydraulic conductivity of the various fractured bedrock units and effective porosities did not appear to be justified by data or assessments from the site. These issues introduced significant uncertainties to assessing how the proposed mine will affect changes in groundwater flow and contaminant travel times, and impacts of these changes to local high VEC water users' streams. As recommended in these guidelines (see Figure 2-2), consultation with government technical staff during the development of the modelling objectives, the conceptual model, and the data collection requirements could have helped to identify these issues and questions much earlier in the modelling process.

Finally, it is emphasized that a numerical groundwater model developed at the EA stage for assessing impacts of proposed mines is most useful for calibrating baseline conditions and performing sensitivity analyses related to predictions, as was done here. As mining operations proceed and additional data become available, the model could be verified.

APPENDIX C-3

CASE STUDY 3 – GROUNDWATER EXTRACTION

REPORT NO. 194001

Case Study 3

Municipal Groundwater Extraction in Southwestern British Columbia

Table of Contents

C3-1 PROJECT OVERVIEW

This groundwater extraction project (the "Project") is situated in the Fraser lowlands of southwestern British Columbia, serving a population of nearly 150,000 residents (Figure 1). The region is host to both urban and agricultural activities. Presently, the municipality draws water from 19 extraction wells in the Abbotsford Sumas aquifer (the "Aquifer") and from several surface water intakes. Four additional extraction wells were recently added to the well field and operate at a rate such that an Environmental Assessment (EA) was not initially required. However, in response to a growing population and a need for emergency supply capacity, the municipal Proponent has proposed that the new wells may need to be operated at a combined pumping rate of up to 300 L/s. Under this new proposal, the increased rate requires that the project undergo an EA. This increased capacity would be sustained for five years, until such time that surface water supply systems could be commissioned.

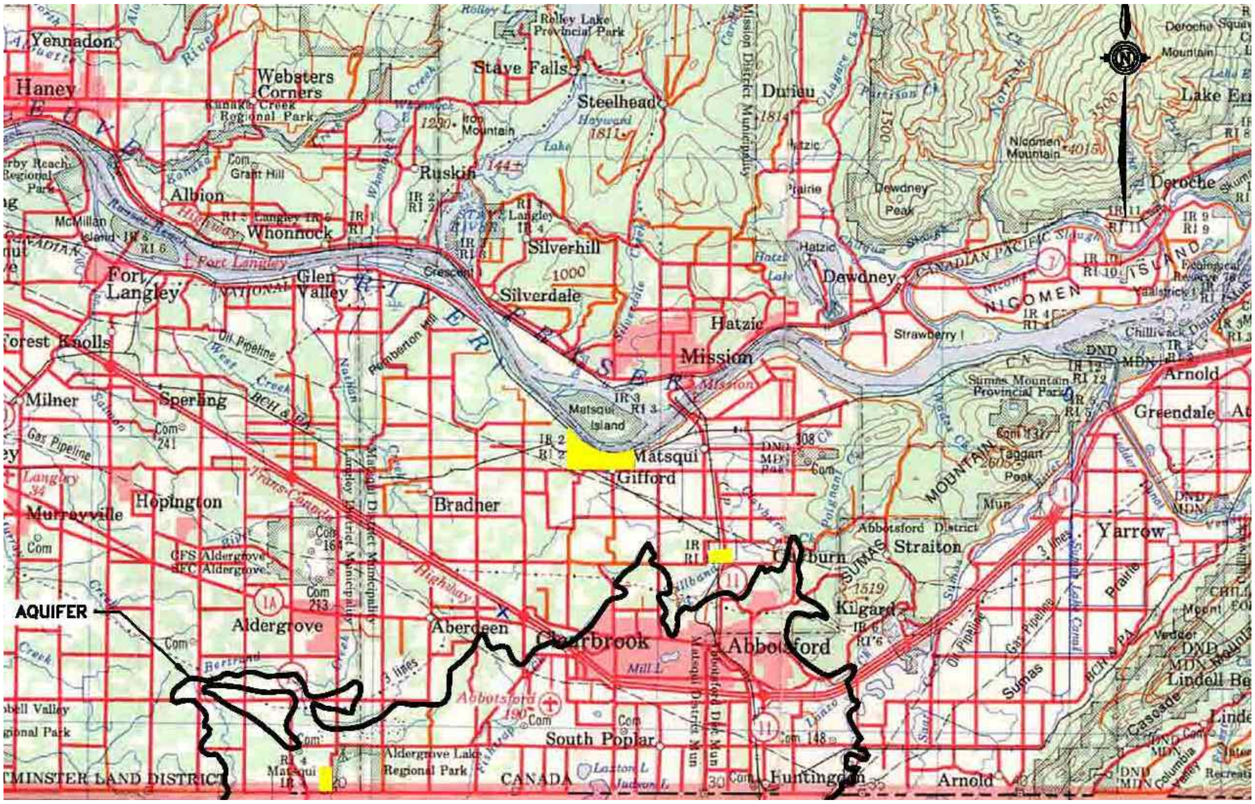


Figure 1: Municipal project site location map for Case Study 3 showing aquifer extent outlined in black.

The unconfined, glaciofluvial sand and gravel source aquifer, which covers an area of approximately 200 km^2, is well understood from previous development of the water supply system and from previous academic research concerning the groundwater system. A hydrogeological consultant was retained to complete a hydrogeological assessment of potential impacts to the aquifer and to the local surface water bodies.

C3-2 MODELLING OBJECTIVES

The objectives of the hydrogeological study and modelling effort were to:

- Assess potential impacts to the aquifer;
- Define the groundwater Zone of Influence (ZOI); and to
- Evaluate impacts to surface water flows and lake water levels.

This would be accomplished with a three-dimensional numerical model for groundwater flow and application of the model to estimate base flow changes.

C3-3 DATA REVIEW

An understanding of the groundwater system was well established at the time of this modelling. A detailed regional groundwater flow model had been previously developed during an earlier investigation of the aquifer.

The data available for this project included geologic maps of the project area, water level monitoring data, production well drilling records and monitoring data, academic research, and additional data collected during the consultant's one-year field program.

The field program included the establishment of groundwater, creek, and lake monitoring stations across the aquifer. Groundwater levels were monitored at 40 locations across the aquifer over a one-year period to assess the seasonal variability of groundwater levels and flow directions, and to investigate groundwater-surface water relationships. Most wells were monitored on a monthly basis. Monitoring locations were selected to maximize spatial coverage across the aquifer, and to complement existing monitoring well networks operated by Environment Canada and BC MOE. Surface water quality sampling was conducted to establish baseline chemical and physical parameters. Field parameters were measured and the samples were retained for laboratory analysis.

Pumping tests were performed in multiple wells across the aquifer over several years of study and confirmed that the source aquifer is a leaky-artesian type. The production records for existing wells were also examined. Estimates of current groundwater extraction rates from the aquifer were based on records of instantaneous flow measurements and yield estimates from operating pumping wells.

Several short-duration studies related to storm-water management provided estimates of creek flows at eight locations in the area and one-year hydrographs were produced for estimates of groundwater baseflow and recharge.

Overall, the project benefits from a well distributed set of monitoring locations, a multi-season monitoring program, and good documentation of historic and current aquifer usage.

C3-4 CONCEPTUAL MODEL

The conceptual model for this groundwater flow modelling exercise is based on the previous understanding of subsurface geology and the hydraulic characteristics of this aquifer.

Analysis of the monitoring program and historic data showed that the water table is sensitive to seasonal variations in the infiltration of precipitation and that water levels are highest in January and lowest in

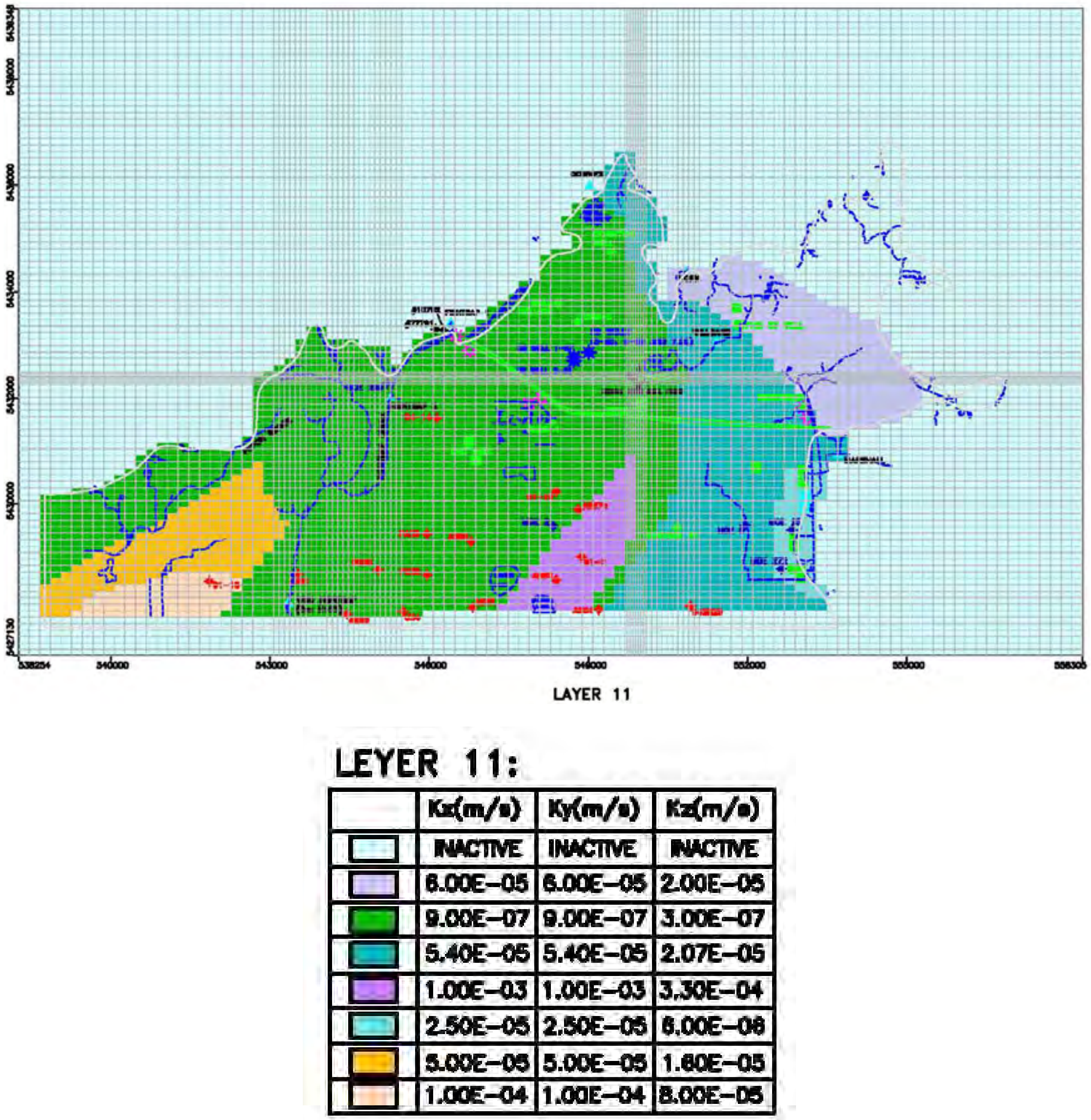
October (which is consistent with regional observations in the B.C. lower mainland). Furthermore, inter-well drawdown caused by pumping of the production wells was evident.

Conceptually, the groundwater flow direction does not change seasonally but the elevation of the water table increases notably during the wet months.

A basic water balance was created, using estimates of precipitation, evapotranspiration, infiltration, run-off, and pumping records. Current extraction from the aquifer is significant and a reasonably robust estimate of current use was determined, albeit uncertain. The water balance showed that only a portion of aquifer recharge was consumed during pumping (33%) and that aquifer storage had not been depleted. Further water balance analysis suggested that the proposed increase in pumping rates (to 38% of recharge) would not negatively impact groundwater storage in the aquifer.

An existing three-dimensional groundwater flow model was used as the basis for this numerical modelling exercise. The model domain was reduced and discretization was refined to focus on the Site's surface water and groundwater systems. The three-dimensional MODFLOW code was used to simulated steady-state and transient flow. The groundwater flow model was calibrated against a spatially and temporally distributed set of observations, including transient calibration to a pumping test. Predictions included an estimate the groundwater zone of influence due to increased withdrawal rates and estimates of baseflow impacts to potentially vulnerable creeks.

Figures 2 and 3 present the distribution of hydrogeologic units assumed for the modelling exercise.



LEYER 11:

	Kx(m/s)	Ky(m/s)	Kz(m/s)
⬜	INACTIVE	INACTIVE	INACTIVE
🟪	6.00E-05	6.00E-05	2.00E-05
🟩	9.00E-07	9.00E-07	3.00E-07
🟦	5.40E-05	5.40E-05	2.07E-05
🟪	1.00E-03	1.00E-03	3.30E-04
🟦	2.50E-05	2.50E-05	6.00E-06
🟧	5.00E-05	5.00E-05	1.60E-05
🟫	1.00E-04	1.00E-04	8.00E-05

Figure 2: Plan view showing distribution of hydrogeologic units in the 3D model (shown here for only Layer 11 as an example). The legend shows anisotropic hydraulic conductivity values for each unit.

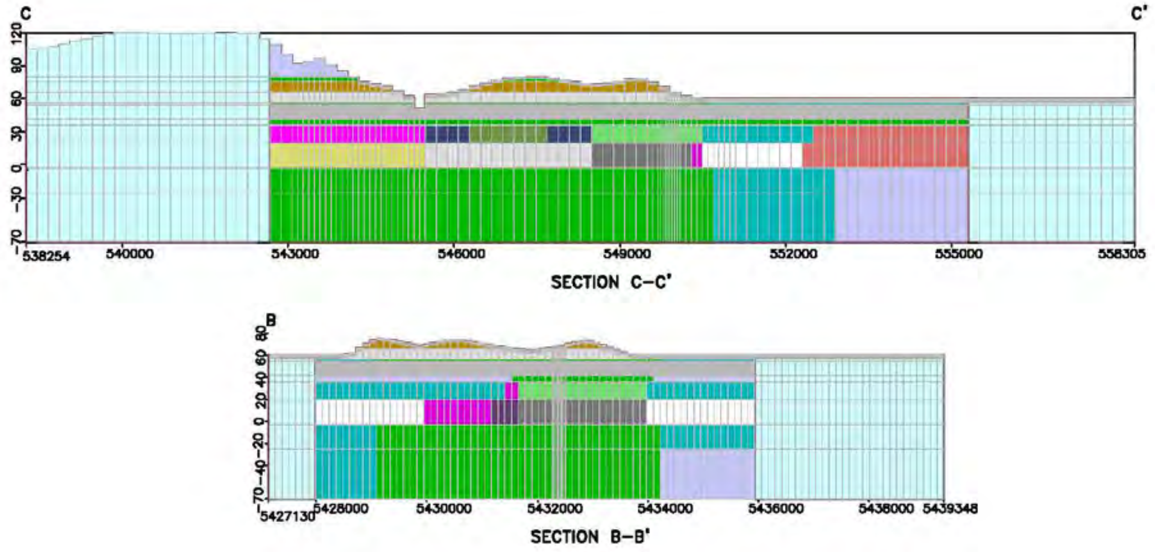


Figure 3: Model sections showing vertical distribution of hydrogeologic units.

C3-5 NUMERICAL MODEL SETUP

The numerical model for this study was based on an existing regional groundwater flow model. The model domain comprises an extensive aquifer that spans the Canada-US border. The current modelling effort focuses solely on the Canadian aquifer component, targeting approximately 80 km^2 of the total aquifer extent. The model domain was further reduced in size based on proximity to the Site, and by removing areas isolated by groundwater flow divides.

The model domain was discretized horizontally into grid cells 200 by 120 metres, consistent with the regional flow model, but was refined in the vicinity of the well field where significant stresses would be applied through pumping. Furthermore, the grid spacing was refined at the location of a potentially vulnerable creek. Vertically, the domain was discretized into 11 layers representing the hydrostratigraphic units identified in the previously developed conceptual model.

A constant-head boundary was simulated along the Canada-US border to simulate outflows to the US portion of the aquifer. Additionally, a constant-head boundary condition was assumed along the southeast model boundary where springs were interpreted to exist. In both cases, the head values were inferred from piezometric contour maps from October and January. A groundwater divide was interpreted at the northeast edge of the model domain; therefore, a no-flow boundary was simulated. The remaining model domain limits were assigned constant-head conditions according to the piezometric contour maps. Figure 4 provides an illustration of these boundary conditions.

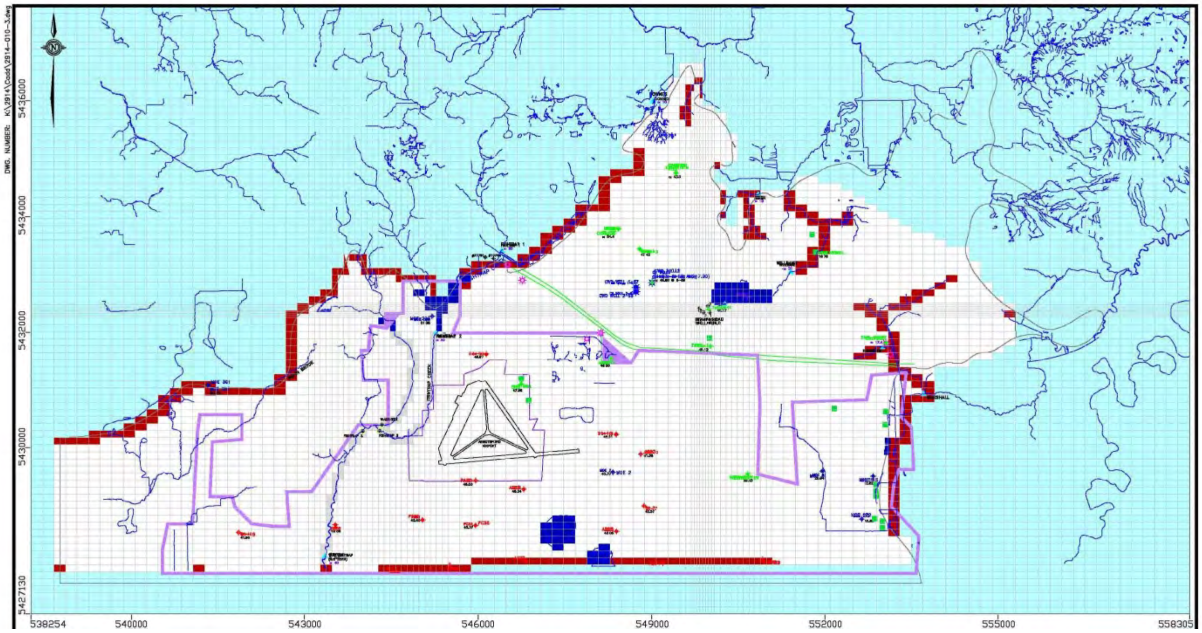


Figure 4: Boundary conditions for the 3D numerical model, showing constant head (red), river/lake (blue), and drain (light grey along streams) boundaries as well as extent of active cells (white).

Creeks and lakes that were interpreted to be perched above the aquifer for most of the year were assigned river boundary conditions, whereas creeks that intercept the aquifer were assigned drain boundaries in MODFLOW. The nodes were assigned a range of conductance values; however, justification for these values is not provided in the documentation reviewed for this case study. In cases where the surface water feature was interpreted to be in constant hydraulic communication with the aquifer, constant head boundaries were assigned.

Assuming a uniform precipitation distribution and a constant infiltration coefficient representative of the overburden materials, the net recharge was calculated for the model. The value was considered to account for less infiltration in urban settings.

The primary sinks in this model include the municipal groundwater extraction wells, industrial supply wells, and groundwater withdrawal for crop irrigation. These withdrawal rates were assumed from pumping records, instantaneous monitoring, and estimation.

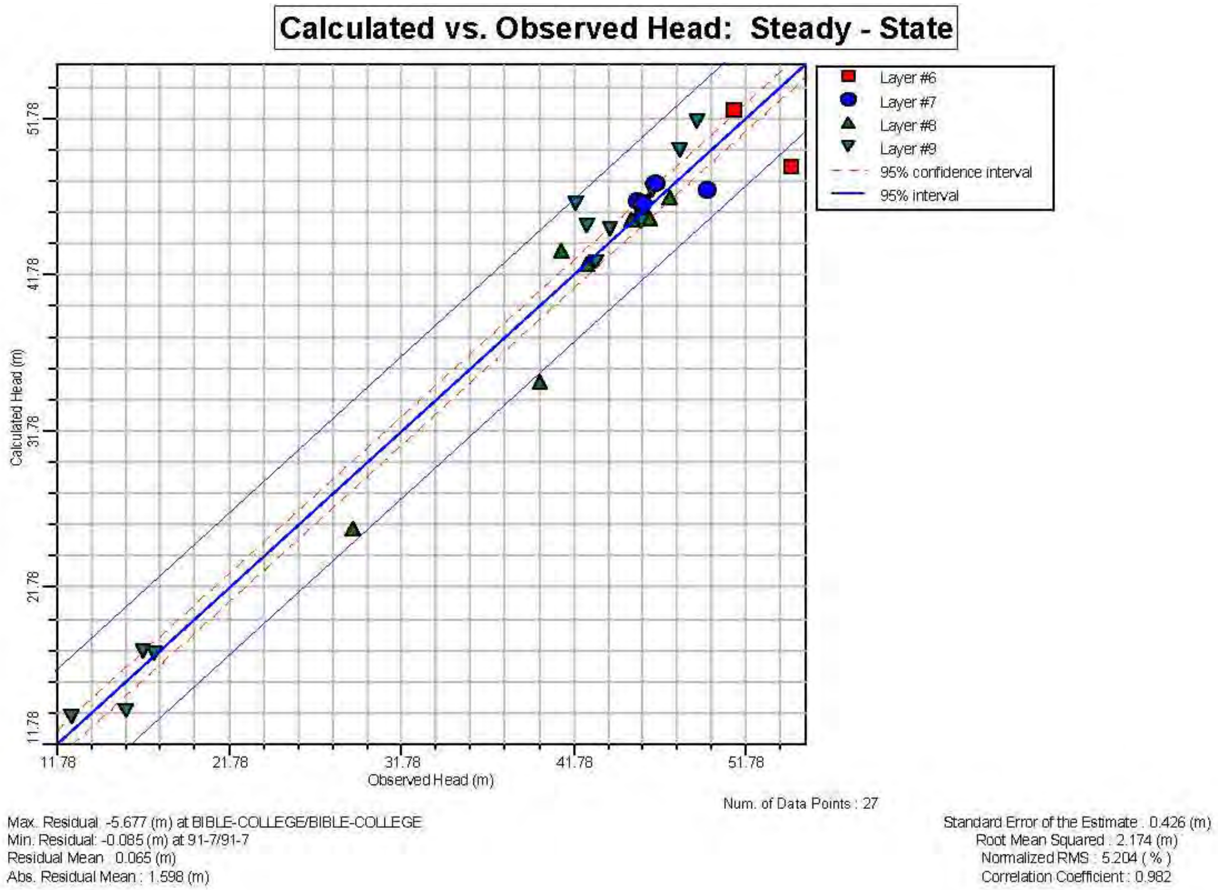
C3-6 MODEL CALIBRATION

The model was calibrated under steady and transient states. The steady state calibration, performed on the basis of hydraulic head observations, was used as the basis for defining the starting hydraulic head distribution for the transient simulations.

The initial transient calibration included simulation of a pumping test completed in the existing well field to determine the aquifer transmissivity and storage properties. Back-simulation of the pumping test was complicated by the presence of other operating wells in the vicinity, and by a limited observation dataset. The drawdown values simulated were deemed reasonably close to the observed values, although no error statistics were provided due to a lack of data.

An additional transient calibration was performed for the entire aquifer. The model was calibrated to seasonal head observations, incorporating the effects of both time-dependent recharge and variable demands on the system due to crop irrigation.

For the steady-state and transient runs, the normalized root-mean-square error (NRMSE) was calculated between 4% and 6%, which was considered acceptable (Figure 5). The seasonal variations were well simulated by the model.



Num. of Data Points : 27

Max. Residual: -5.677 (m) at BIBLE-COLLEGE/BIBLE-COLLEGE
Min. Residual: -0.085 (m) at 91-7/91-7
Residual Mean : 0.065 (m)
Abs. Residual Mean : 1.598 (m)

Standard Error of the Estimate : 0.426 (m)
Root Mean Squared : 2.174 (m)
Normalized RMS : 5.204 (%)
Correlation Coefficient : 0.982

Figure 5: Example of model calibration reporting showing goodness of simulation fit and residual statistics (including geographic locations of maximum and minimum residuals)

The groundwater flow model was further calibrated by comparing simulated groundwater discharge to the creeks against estimates from manual monitoring. Aquifer properties were varied until groundwater inflows were within 15% of the measured values.

C3-7 MODEL PREDICTIONS & SENSITIVITY ANALYSES

Two predictive transient runs were completed for the base case project scenario (pumping for 100 days at 290 L/s) and for a more conservative scenario (pumping for 120 days at 290 L/s). The zone of influence for each scenario was established based on the pre-determined minimum drawdown criteria of 10 centimetres. Figure shows the zone of influence in plan view.

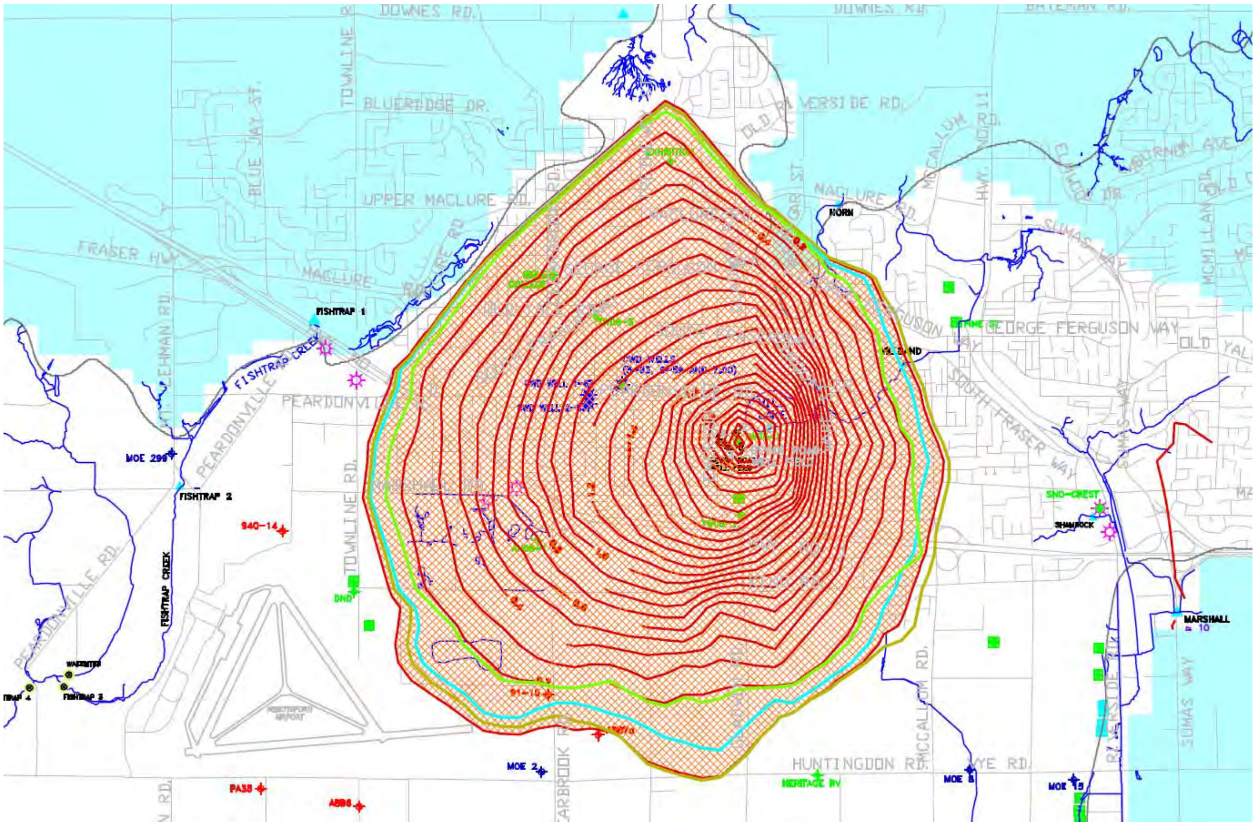


Figure 6: Zone of Influence for groundwater extraction at 290 L/s. The blue and green zone borders indicate the predicted maximum extents determined through sensitivity analyses.

The reduction in creek baseflow was calculated based on the difference in zone budget calculations for the baseline transient simulation and the two predictive scenarios. The surface watercourses closest to the well field were simulated to experience the most significant reduction in flows. As two of the creeks were predicted to experience a reduction greater than the agreed Trigger Level of 10%, further investigation was recommended. As the lakes in the area are interpreted to be perched above the groundwater table, no significant impacts from pumping were anticipated.

Sensitivity analyses were conducted to determine the prediction sensitivity to uncertainty in the hydraulic conductivity and aquifer storage parameters. Where a lower and upper bound estimates were supported by field data, the aquifer parameters were adjusted to produced lower and upper bound predictions. The results of the sensitivity analysis showed a change in the hydraulic gradients in the well field; however, there was no significant change in the extent of the groundwater zone of influence. The creeks identified for further investigation in the initial predictive runs were again shown to exceed the Trigger Level for baseflow reduction in both the upper bound and lower bound cases. Again this was a result of the proximity of those creeks to the well field and to the aquifer zones which were manipulated during the sensitivity analysis.

A cumulative effects assessment regarding the loss of aquifer recharge due to future land development was deemed unnecessary by the consultant.

C3-8 TRANSPORT MODELLING

Transporting modelling was not completed for this groundwater extraction project.

C3-9 CASE STUDY EVALUATION

This modelling exercise benefited from refining a regional aquifer model to simulate groundwater flow within a smaller domain that was anticipated to potentially be influenced by the proposed extraction wells. In this case, the modeller was successful in achieving the modelling objectives for this project.

This model benefitted greatly from both steady-state and transient calibrations, with stresses in the transient calibration reflective of the anticipated stresses applied to the aquifer during operations (pumping).

Results of the calibration process were only presented for the final model, and only in the form of observed vs. calculated head residuals. Spatial distribution of residuals was not presented, nor calibration sensitivity statistics.

Validation was defined as comparing groundwater discharge to creeks for the calibrated model and observations. During this validation aquifer properties were adjusted. The model was verified against an additional dataset, such as records from active operation of the well field, which commenced in July 2009 at a lower extraction rate (75 L/s) than proposed for the Project (290 L/s). .

A baseline transient model was used to model the pre-project aquifer groundwater system, which was then used to assess the change in groundwater conditions (from baseline) as a result of the project. Furthermore, a sensitivity analysis on predictive models resulted in the adoption of both a project base case and upper bound case as results.

Uncertainty analyses did not include river, lake or stream conductance values.

The modeller has presented several key assumptions for this study, namely:

- Each layer is assumed to be continuous in areal extent, but its geometry is not always congruent with a geologic formation
- The aquifer extends uniformly across the Canada-US border and groundwater outflows occur along the border
- The only source of recharge to the model is direct precipitation, which is uniformly distributed over the model domain

Furthermore, the modeller indicates that the primary sources of uncertainty in the model are identified as:

- Limited reliable information on aquifer properties
- Limited information regarding boundary conditions
- Limited understanding of the distribution of recharge across the aquifer
- Incomplete records of current groundwater usage (particularly crop irrigation)

Due to these assumptions and limitations, the model cannot perfectly represent the actual domain; however, calibration and sensitivity analyses were used to demonstrate that the model was capable of simulating observed flow behaviour in the aquifer and that the level of uncertainty did not jeopardize confidence in the model predictions.

APPENDIX D

MODELLING & MODEL REVIEW CHECKLISTS

TABLE D1 - MODEL APPRAISAL (modified from MDBC, 2001)

Page 1 of 2

#	Question	N/A	Missing	Deficient	Adequate	Comments
1.0	**THE REPORT**					
1.1	Does the modeling report describe all pertinent aspects of the modeling study (see section 10 of BC MoE modeling guidelines)?					
1.2	Are the objectives of the model study clearly defined?					
1.3	Has the modeling study satisfied project objectives?					
1.4	Are modeling methods and results presented in a clear, transparent manner and in sufficient detail to allow an independent assessment of model study findings?					
1.5	Are conclusions supported by the modeling results?					
1.6	Are recommendations reasonable and supported by the modeling results?					
2.0	**DATA COLLECTION & ANALYSIS**					
2.1	Is collection and analysis of site characterization data (geophysics, drilling, well installation, hydraulic testing etc) adequate for the modeling objective?					
2.2	Is collection and analysis of groundwater monitoring data (water levels, water quality) adequate for the modeling objective?					
2.3	Are observed groundwater levels and inferred contour plan and flow directions presented?					
2.4	Have all the potential recharge data (rainfall, streamflow, irrigation, floods, etc.) been collected and analysed?					
2.5	Have all potential discharge data been collected and analysed? (abstraction, evapotranspiration, drainage, springflow, etc.)					
2.6	Have the recharge and discharge datasets been analysed for their seasonal groundwater response?					
2.7	Has aquifer response to transient hydraulic stresses (pumping, U/G development, pit excavation, tailings discharge etc) been monitored and analysed?					
3.0	**CONCEPTUALISATION**					
3.1	Is the conceptual model adequately described and visualized (maps, schematics, block diagrams etc)?					
3.2	Is the conceptual model consistent with project objectives and the required model complexity?					
3.3	Is the conceptual model consistent with available field data?					
3.4	Does the conceptual model miss any key process(es)?					
4.0	**MODEL DESIGN**					
4.1	Is the spatial extent of the flow (and transport) model appropriate?					
4.2	Are the applied boundary conditions for flow (and transport) plausible and unrestrictive?					
4.3	Is the flow solution used for transport modeling approriate and consistent with the transport problem?					
4.4	Are proposed resource developments (e.g. pumping, open pit mining etc) properly implemented in flow (and transport) model?					
4.5	Is the modeling software appropriate for the objectives of the study?					

TABLE D1 - MODEL APPRAISAL (modified from MDBC, 2001) **Page 2 of 2**

#	Question	N/A	Missing	Deficient	Adequate	Comments
5.0	**CALIBRATION**					
5.1	Is the process of model calibration transparent and follows accepted practice?					
5.2	Is the flow model sufficiently calibrated against spatial observations?					
5.3	Is the flow model sufficiently calibrated against temporal observations?					
5.4	Is the transport model sufficiently calibrated?					
5.5	Are calibrated parameter distributions and ranges plausible?					
5.6	Does the calibration statistic satisfy acceptable (or agreed) performance criteria?					
5.7	Are there good reasons for not meeting acceptable (or agreed) performance criteria?					
5.8	Has a post-calibration sensitivity analysis been performed to evaluate the uncertainty in model prediction?					
6.0	**VERIFICATION**					
6.1	Is verification of the flow (or transport) model satisfactory?					
6.2	Does the reserved dataset include stresses consistent with the model prediction scenarios?					
6.3	Are there good reasons for an unsatisfactory verification?					
7.0	**PREDICTION**					
7.1	Are simulated hydraulic stresses reasonable and representative of proposed resource developments (e.g. location and duration of mine development)?					
7.2	Have multiple scenarios been run to cover the full range of alternative development (or closure) scenarios?					
7.3	Is the time horizon for prediction comparable with the length of the calibration/verification period?					
7.4	Is the spatial scale (area, depth) for flow predictions comparable to the area covered by model calibration/verification?					
7.5	Are all important CoCs included in transport predictions?					
7.6	Are all potential sources of CoCs (e.g. seepage from TSF & WRD) included in model predictions?					
7.7	Are the model predictions plausible?					
7.8	Has a predictive sensitivity analysis been completed to evaluate the reliability of model predictions?					
8.0	**UNCERTAINTY ANALYSIS**					
8.1	Has a sensitivity analysis been performed to quantify the uncertainty in model calibration and model predictions?					
8.2	Has a sensitivity analysis been performed to evaluate uncertainty in predicted groundwater flow?					
8.3	Has a sensitivity analysis been performed to evaluate uncertainty in predicted contaminant transport?					
8.4	Is the sensitivity analysis sufficiently intensive for key parameters?					
8.5	Are uncertainties in future project developments (e.g. scope or timing of mine plan) evaluated in predictive sensitivity analysis?					
8.6	Has a "reasonable upper bound" condition been included in the predictive sensitivity analysis?					

TABLE D2 - CHECKLIST FOR MODEL COMPLIANCE (modified from MDBC, 2001)

#	Question	PASS	FAIL	IF PASS: COMMENT	IF FAIL: CORRECTIVE ACTION REQUIRED
1	Does the modeling report present all aspects of the modeling study (see BC MoE modeling guidelines)?				
2	Are the objectives of the model study stated clearly?				
3	Are the modeling objectives satisfied?				
4	Are available field data adequate to meet modeling objectives? If data gaps have been identified, are they adequately addressed by way of uncertainty analysis?				
5	Is the conceptual model consistent with project objectives and model complexity?				
6	Is the conceptualisation based on a competent analysis of all available data and presented clearly?				
7	Does the conceptual model include all relevant aspects of the flow and transport problem to be evaluated ?				
8	Does model design/implementation conform with best practice (see BC modeling guidelines)?				
9	Is model calibration satisfactory?				
10	Are calibrated model parameters (aquifer properties, recharge etc) plausible? If applicable, are transport parameters plausible?				
11	Does model prediction/application conform with best practice (see BC modeling guidelines)?				
12	Has a sensitivity/uncertainty analysis been completed to illustrate uncertainty in model calibration & model predictions?				

TABLE D3 - PEER REVIEW: REPORT CHECKLIST (modified from MDBC, 2001)

Page 1 of 9

#	Question	N/A	Missing	Deficient	Adequate	Comments
1.1	Is a modeling report provided?					
1.2	Are relevant prior or companion reports provided or accessible?					
1.3	Does the modeling report describe all pertinent aspects of the modeling study (see section 10 of BC MoE modeling guidelines)?					
1.4	Is there a clear statement of project objectives?					
1.5	Is the proposed resource project described in sufficient detail?					
1.6	Is the level of model complexity clear and justified?					
1.7	Has the modeling study satisfied project objectives?					
1.8	Are modeling methods and results presented in a clear, transparent manner and in sufficient detail to allow an independent assessment of model study findings?					
1.9	Would it be possible to re-create the structure of the model from what is reported?					
1.10	Is it clear which person(s) did the modelling?					
1.11	Does the modeling report discuss model convergence and model error (water balance error, mass balance error, etc.)?					
1.12	Are modeling input/output files available for a model audit?					
1.13	Are all data sources properly referenced and/or included in report (in Appendix)?					
1.14	Does the modeling report discuss model uncertainty and its influence on model predictions?					
1.15	Are conclusions supported by the modeling results?					
1.16	Are recommendations reasonable and supported by the modeling results?					
1.17	Are the model results of any practical use?					

TABLE D3 - PEER REVIEW: DATA ANALYSIS CHECKLIST (modified from MDBC, 2001)

#	Question	N/A	Missing	Deficient	Adequate	Comments
2.1	Have prior investigations been examined and acknowledged?					
2.2	Is current knowledge sufficient for a mathematical model?					
2.3	Is there a cost-effective alternative to modeling which would satisfy the project objectives?					
2.4	Has a literature review been completed?					
2.5	Does hydrogeological characterization program (geophysics, drilling, hydraulic testing) cover entire project area(s)?					
2.6	Has there been emphasis on identifying/characterizing preferential flow paths?					
2.7	Does hydrogeological characterization program (geophysics, drilling, hydraulic testing) cover all major aquifer units?					
2.8	Are geophysics and drilling data reliable and correctly interpreted?					
2.9	Has structural mapping and/or a structural analysis of major bedrock aquifer units in the project area been completed and analysed?					
2.10	Has hydraulic testing (packer testing, slug testing, single well/multiple well pumping tests) been completed at the approriate scale (in space and time) and analysed?					
2.11	Have temporal trends in groundwater levels (hydrographs) been monitored and analysed?					
2.12	Are contour maps of inferred water table/potentiometric surface(s) and inferred directions of groundwater flow presented and analysed?					
2.13	Has hydraulic testing (packer testing, pumping tests) and/or groundwater level monitoring been completed to determine the hydraulic properties of important bedrock structures?					
2.14	Has precipitation (rainfall/snowfall) data been collected and analysed?					
2.15	Has snowmelt data been collected and analysed?					
2.16	Has streamflow data been collected and analysed?					
2.17	Has evapotranspiration data been collected and analysed?					
2.18	Has groundwater usage (pumping) data been collected and analysed?					
2.19	Has groundwater response to the above hydraulic stresses been analysed?					
2.20	Has aquifer response to project-related stresses (pumping, U/G development, pit excavation, tailings discharge etc) been monitored and analysed?					
2.21	Has groundwater quality been monitored and analysed (using time trend plots, piper plots, scatter diagrams, etc)					
2.22	Has groundwater quality been interpreted (e.g. to differentiate aquifer units, determine flow paths and/or distinguish contaminant sources)?					
2.23	Has permafrost data been collected and analysed?					
2.24	Is the designation of 'outlier' values reasonable?					
2.25	Has any relevant dataset been ignored?					

TABLE D3 - PEER REVIEW: CONCEPTUAL MODEL CHECKLIST (modified from MDBC, 2001)

#	Question	N/A	Missing	Deficient	Adequate	Comments
3.1	Is there a clear description of the conceptual model?					
3.2	Is there a graphical representation of the conceptual model?					
3.3	Are multiple plausible conceptual models considered?					
3.4	Is the conceptual model consistent with the project objectives and the required model complexity?					
3.5	Are VECs emphasized in conceptual model development?					
3.6	Is the conceptual model consistent with prior knowledge?					
3.7	Is the conceptual model consistent with available field data?					
3.8	Is the conceptual model unnecessarily simple?					
3.9	Are simplifying assumptions in the conceptual model justified and defensible?					
3.10	Is the conceptual model unnecessarily complex?					
3.11	If any possible key process is missing, is the justification adequate?					
3.12	Does the conceptual model include a water balance for the GW system?					
3.13	Are limitations and uncertainties in conceptual model described?					
3.14	Does the conceptual model address contaminant transport?					
3.15	Does the conceptual model address the influence of aquifer heterogeneity on solute transport?					
3.16	Does the conceptual model address the scale effect of dispersion on solute transport ?					
3.17	Does the conceptual model miss any key process(es)?					
3.18	Has the conceptual model been updated throughout the modeling project?					
3.19	Has the conceptual model been reviewed independently?					

TABLE D3 - PEER REVIEW: MODEL DESIGN CHECKLIST (modified from MDBC, 2001)

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#	Question	N/A	Missing	Deficient	Adequate	Comments
4.0	**A. Groundwater Flow Model**					
4.1	Is the choice of mathematical model for flow (analytical vs numerical; saturated vs partially saturated) consistent with project objectives and conceptual model?					
4.2	Is the choice of software code & GUI appropriate?					
4.3	Is the software in common use and accessible to reviewers?					
4.4	Is the spatial extent of the flow model domain appropriate?					
4.5	Is the horizontal discretization of the flow model appropriate?					
4.6	Is the vertical discretization of the flow model approriate?					
4.7	Is the discretization for the flow model refined where appropriate?					
4.8	Are atmospheric stresses (recharge/ET) appropriately implemented in flow model?					
4.9	Are internal sinks/sources approriately implemented in flow model?					
4.10	Are boundary conditions in flow model plausible and unrestrictive?					
4.11	If steady-state flow conditions are simulated, is this assumption reasonable?					
4.12	If transient flow behaviour is simulated, are the stress periods reasonable?					
4.13	Is the number of time steps per stress period justified?					
4.14	Are the initial conditions for transient simulations defensible?					
4.15	Has proposed GW resource development (pumping) been properly implemented in numerical flow model?					
4.16	Has proposed mining development (open pit, tailings impoundment, waste rock pile) been properly implemented in numerical flow model?					
4.17	Is the model accuracy acceptable (ie. Are convergence criteria for flow solution disclosed and appropriate)					

TABLE D3 - PEER REVIEW: MODEL DESIGN CHECKLIST (modified from MDBC, 2001)

#	Question	N/A	Missing	Deficient	Adequate	Comments
4.0	**B. Transport Model**					
4.18	Is the choice of transport model (i.e. analytical vs numerical; pathline analysis vs solute transport) consistent with project objectives and conceptual model?					
4.19	Is the choice of the transport solution method (e.g. finite difference, method of characteristics) acceptable for the project objectives?					
4.20	Is the flow solution used for transport modeling appropriate and consistent with the transport problem?					
4.21	Has the flow model used for transport been calibrated?					
4.22	Is the model domain appropriate for the transport problem?					
4.23	Is the horizontal discretization of the transport model appropriate?					
4.24	Is the vertical discretization of the transport model appropriate?					
4.25	Is the discretization of the tranport model refined where appropriate?					
4.26	Does the flow & transport model adequately represent preferential flow paths due to aquifer heterogeneity?					
4.27	Does the transport model adequately represent scale-effects of solute dispersion?					
4.28	Are boundary conditions in transport model plausible and unrestrictive?					
4.29	Are boundary conditions in flow model consistent with boundary conditions in transport model?					
4.30	Have potential source terms of CoC (e.g. concentration/load in seepage from TSF) been adequately implemented in transport model					
4.31	Have potential sink terms of CoC (e.g. concentration/load recovered in drains, recovery wells, etc.) been adequately implemented in transport model					
4.32	Are reactive transport processes (sorption, precipitation/dissolution, degradation) appropriately implemented?					
4.33	Are the initial concentrations of the CoC reasonable?					
4.34	Are the transport time steps reasonable?					
4.35	Is the accuracy of the transport algorithm acceptable (ie. Is numerical dispersion and/or oscillation acceptable)					

TABLE D3 - PEER REVIEW: CALIBRATION CHECKLIST (modified from MDBC, 2001)

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#	Question	N/A	Missing	Deficient	Adequate	Comments
5.0	**A. Groundwater Flow Model**					
5.1	Is sufficient head/flow data available for spatial calibration?					
5.2	Is sufficient head/flow data available for temporal calibration?					
5.3	Is the process of model calibration transparent and follows accepted practice (see section 7 of BC MoE guidelines)?					
5.4	Is it clear whether calibration is automated or trial-and-error?					
5.5	Does the model meet covergence criteria and is the water balance error acceptable?					
5.6	Are estimates of groundwater discharge (e.g. drain flow, mine inflow, spring flow, stream baseflow) included as calibration targets					
5.7	Do the calibration statistic(s) satisfy acceptable (or agreed) performance criteria?					
5.8	Are there good reasons for not meeting acceptable (or agreed) performance criteria?					
5.9	Are calibrated parameter distributions and ranges plausible?					
5.10	Are 'outlier' values adequately addressed during flow model calibration?					
5.11	Is the model calibrated to data from different hydrological regimes?					
5.12	Is the model sufficiently calibrated against spatial observations?					
5.13	Is the model sufficiently calibrated against temporal observations?					
5.14	Does the model calibration show a systematic bias (in space and/or time)?					
5.15	Is the model overparameterized?					
5.16	Has a sensitivity analysis been completed using the calibrated flow model?					
5.0	**B. Transport Model**					
5.17	Is sufficient water quality data available for spatial calibration?					
5.18	Is sufficient water quality data available for temporal calibration?					
5.19	Are calibration methods of the transport model described and transparent?					
5.20	Have formal (quantitative) performance criteria been adopted for calibration of transport model?					
5.21	If so, does model calibration satisfy acceptable (or agreed) performance criteria?					
5.22	Is the model sufficiently calibrated against spatial observations?					
5.23	Is the model sufficiently calibrated against temporal observations?					
5.24	Is the solute mass balance error acceptable?					
5.25	Does the model calibration show a systematic bias (in space and/or time)?					
5.26	Are calibrated parameter distributions and ranges plausible?					
5.27	Are 'outlier' values adequately addressed during transport model calibration?					
5.28	Does the model calibration show a systematic bias (in space and/or time)?					
5.29	Has a sensitivity analysis been completed using the calibrated transport model?					

TABLE D3 - PEER REVIEW: VERIFICATION CHECKLIST (modified from MDBC, 2001)

#	Question	N/A	Missing	Deficient	Adequate	Comments
6.0	**A. Groundwater Flow Model**					
6.1	Is the process of model verification transparent and follows accepted practice (see section 7 of BC MoE guidelines)?					
6.2	Has head/flow data been reserved for a verification exercise?					
6.3	Is the reserved head/flow dataset an extension of the time period?					
6.4	Is the reserved head/flow dataset taken from a subset of monitoring points (e.g. wells) not used for calibration?					
6.5	Is the reserved head/flow dataset from a different hydrological regime?					
6.6	Is the volume/quality of reserved data sufficient to establish verification?					
6.7	Is verification of the flow model judged to be satisfactory?					
6.8	Are there good reasons for an unsatisfactory verification?					
6.9	Does model verification indicate systematic biases (in space and/or time)?					
6.10	Does the reserved head/flow dataset used for model verification include stresses consistent with the prediction scenarios?					
6.11	If steady state and transient simulations were completed, do overlapping periods agree?					
6.0	**B. Transport Model**					
6.11	Has concentration data been reserved for a verification exercise?					
6.12	Is the reserved concentration dataset an extension of the time period?					
6.13	Is the reserved concentration dataset taken from a subset of monitoring points (e.g. wells) not used for calibration?					
6.14	Is the reserved concentration dataset from a different hydrological regime?					
6.15	Is the volume/quality of reserved data sufficient to establish verification?					
6.16	Is verification of the transport model judged to be satisfactory?					
6.17	Are there good reasons for an unsatisfactory verification?					
6.18	Does model verification indicate systematic biases (in space and/or time)?					
6.19	Does the reserved concentration dataset used for model verification include stresses consistent with the prediction scenarios?					

TABLE D3 - PEER REVIEW: PREDICTION CHECKLIST (modified from MDBC, 2001) **Page 8 of 9**

#	Question	N/A	Missing	Deficient	Adequate	Comments
7.0	**A. Groundwater Flow Model**					
7.1	Are flow predictions made for steady state flow conditions?					
7.2	Are flow predictions made for transient flow conditions?					
7.3	Are simulated hydraulic stresses reasonable and representative of proposed resource developments (e.g. location and duration of mine development)?					
7.4	Is the time horizon for flow prediction comparable with the length of the calibration / verification period?					
7.5	Is the spatial scale (area, depth) for flow predictions comparable to the area covered by model calibration/verification?					
7.6	Have multiple scenarios been run to cover the full range of alternative development (or closure) scenarios?					
7.7	Have multiple scenarios been run for climate variability and/or climate change?					
7.8	Is the water balance error for predictive runs discussed and acceptable?					
7.9	Are the flow predictions plausible (e.g. extent of drawdown, mine inflow)?					
7.10	Are flow predictions likely to be impacted by constraining boundary conditions?					
7.11	If boundary conditions affect the predictions, are the flow predictions defensible?					
7.12	Has a predictive uncertainty analysis been completed for flow predictions?					
7.0	**B. Transport Model**					
7.13	Are all important CoCs included in transport predictions?					
7.14	Are all potential sources of CoCs (e.g. seepage from TSF & WRD) included in model predictions?					
7.15	Are simplifying assumptions used for transport predictions (e.g. conservative transport or fixed source concentrations) applicable for future predictions ?					
7.16	Does the spatial discretization (horizontal and vertical grid spacing) of the transport model account for future plume migration?					
7.17	Is the flow solution used for transport predictions appropriate and consistent with the transport problem (e.g. steady-state flow for plume migration)?					
7.18	Is the time horizon for transport prediction comparable with the length of the calibration / verification period?					
7.19	Is the spatial scale (area, depth) for transport predictions comparable to the area covered by model calibration/verification?					
7.20	Are transport predictions likely to be impacted by constraining boundary conditions?					
7.21	If boundary conditions affect the predictions, are the transport predictions defensible?					
7.22	Have multiple transport scenarios been run for alternative development (or closure) scenarios?					
7.23	Is the solute mass balance error for predictive runs discussed and acceptable?					
7.24	Are load balances for simulated CoCs presented and discussed?					
7.25	Are transport predictions (e.g. plume extent, contaminant loads, etc.) plausible?					
7.26	Has a predictive uncertainty analysis been completed for transport predictions?					

TABLE D3 - PEER REVIEW: UNCERTAINTY ANALYSIS CHECKLIST (modified from MDBC, 2001)

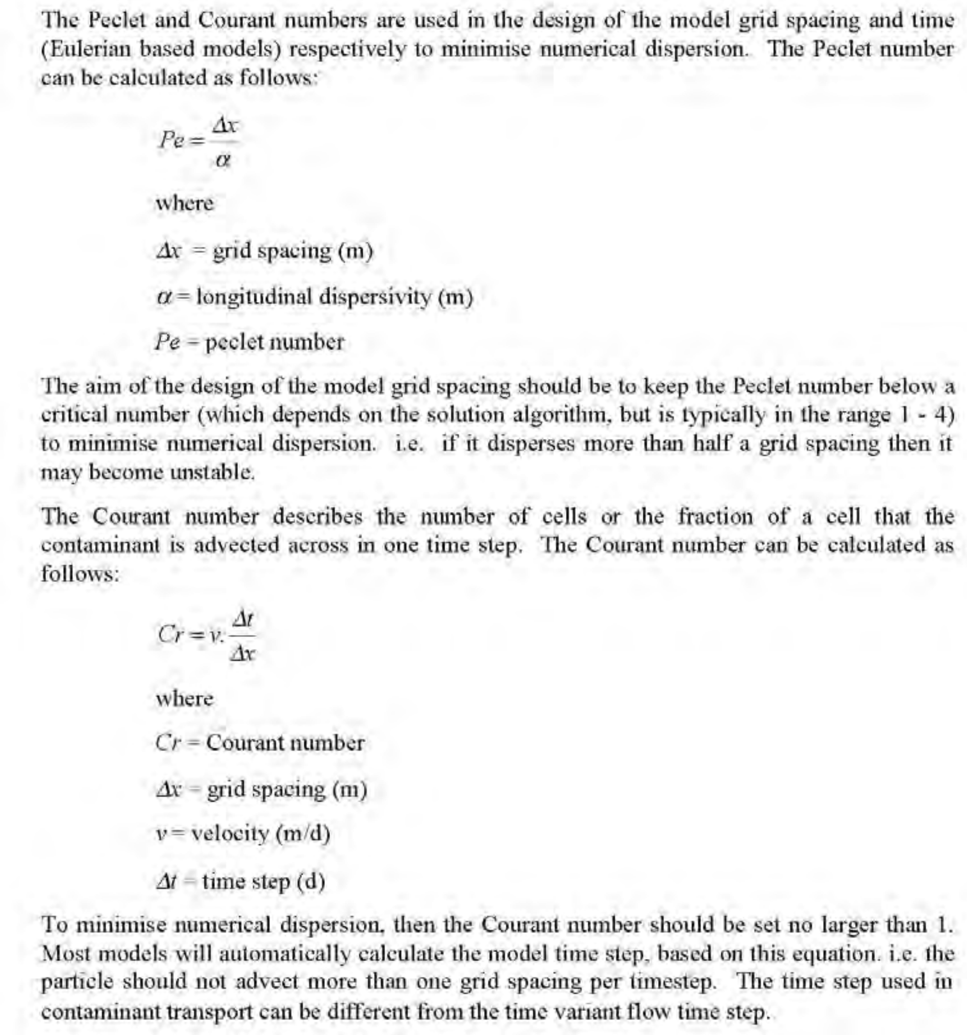
Page 9 of 9

#	Question	N/A	Missing	Deficient	Adequate	Comments
8.1	Is there a discussion of qualitative sensitivities found during calibration?					
8.2	Has a post-calibration sensitivity analysis been performed?					
8.3	Is the sensitivity analysis sufficiently intensive for key parameters?					
8.4	Does the sensitivity analysis address the uncertainty in the conceptual model (e.g. different zonation, hypothetical fault, etc.)?					
8.5	Is there a graphical presentation of sensitivity behaviour?					
8.6	Are sensitivities classified as Type I to Type IV (see section 8 of BC MoE guidelines)?					
8.7	Has a Type IV sensitivity been recognised?					
8.8	Is there a list of ranked sensitivity coefficients?					
8.9	Are sensitivity results used to qualify the reliability of model calibration?					
8.10	Has a sensitivity analysis been performed to evaluate uncertainty in predicted groundwater flow?					
8.11	Has a sensitivity analysis been performed to evaluate uncertainty in predicted contaminant transport?					
8.12	Is the predictive sensitivity analysis sufficiently intensive for key parameters?					
8.13	Is there a graphical presentation of the predictive sensitivity behaviour?					
8.14	Are uncertainties in future project developments (e.g. scope or timing of mine plan) evaluated in predictive sensitivity analysis?					
8.15	Has a "reasonable upper bound" condition been included in the predictive sensitivity analysis?					
8.16	Does the assumed "reasonable upper bound" condition adequately reflect the overall uncertainty in system behaviour?					

APPENDIX E

PECLET AND COURANT NUMBERS

(Reproduced from NGCLC, 2001)



The Peclet and Courant numbers are used in the design of the model grid spacing and time (Eulerian based models) respectively to minimise numerical dispersion. The Peclet number can be calculated as follows:

$$Pe = \frac{\Delta x}{\alpha}$$

where

Δx = grid spacing (m)

α = longitudinal dispersivity (m)

Pe = peclet number

The aim of the design of the model grid spacing should be to keep the Peclet number below a critical number (which depends on the solution algorithm, but is typically in the range 1 - 4) to minimise numerical dispersion. i.e. if it disperses more than half a grid spacing then it may become unstable.

The Courant number describes the number of cells or the fraction of a cell that the contaminant is advected across in one time step. The Courant number can be calculated as follows:

$$Cr = v.\frac{\Delta t}{\Delta x}$$

where

Cr = Courant number

Δx = grid spacing (m)

v = velocity (m/d)

Δt = time step (d)

To minimise numerical dispersion, then the Courant number should be set no larger than 1. Most models will automatically calculate the model time step, based on this equation. i.e. the particle should not advect more than one grid spacing per timestep. The time step used in contaminant transport can be different from the time variant flow time step.

APPENDIX F

CALIBRATION TARGET QUALITY DATA

TABLE F1: Calibration Target Head Data Quality Considerations

Uncertainty Source	Description
Representative water level:	Representativeness of water level of the hydrostratigraphic unit is an important issue in groundwater modelling, particularly in fractured rock aquifers and heterogeneous aquifers. Not all monitoring wells and piezometers are installed in representative locations and depths such that the heads are equilibrated rapidly with the aquifer conditions. For example, some monitoring piezometers may be screened in low permeability sediment lenses within more permeable larger aquifer, causing a slow response time, and may not even be equilibrated at the time of measurement to the aquifer head values (e.g. water levels may be too high due to drilling waters filling the hole or be too low after piezometer purging and sampling). In fractured rocks, some monitoring points may be installed in poorly connected fractures, or fractures affected by local water circulation patterns and recharge, particularly in steep terrain slopes, resulting in measured heads tens of meters different than the interconnected fractured aquifer heads nearby. Even with good site knowledge and good quality control on piezometer installation and measurement, the modeller may not be aware of all errors of this type. The only way to minimize such errors is to have denser observation network and multi level monitoring wells, where anomalous measurements will become apparent compared to the nearby points.
Transient variation of hydraulic head:	Hydraulic heads at any point in the hydrogeological system are never static. Most real sites experience seasonal recharge variation which causes some degree of groundwater level variation, from few centimetres to more than 10m. There are rainfall and snowmelt "events", some very dominant (e.g. winter snowmelt freshet, autumn rain season), and many types of high frequency variation (atmospheric pressure changes affecting unconfined aquifer, tides near sea shores). Long term variation may be important such as climate variation, long term anthropogenic effects (e.g. aquifer pumping, damming of water bodies). Hydraulic heads at observation points should be selected and measured such that transient variation is minimized. If seasonal variation is very important, the water levels across the site should be all measured at the same time (within a few days) to represent the same sate of the hydrogeological system. The type of transient variation should be examined where possible and error bounds specified for the purpose of calibration. The reason is that at some sites the magnitude and direction of hydraulic gradient changes at least seasonally, and the mismatch of times of measurement of observations points may result in different interpretation of flow direction and cause error in model predictions.
Positional survey error:	Almost all hydraulic head data sets contain position errors and this error should not be underestimated even in the times of high precision surveying equipment, Lidar mapping of ground surface, and large databases. At many natural resource sites, the monitoring piezometers are surveyed after the initial water level measurements were taken, and the water elevation may be calculated to initial, or worse, planned, borehole coordinates, and initial elevations may be taken from topographic map contours or hand held GPS units, with elevation accuracy of as bad as 30m, even if there is high precision ground survey available at the site. The error arises from data mismanagement and lack of quality control during field work and early data processing, work which could have been done years before the modeller (often working for a different company) compiles the data for the model. Old water level data may include larger survey error due to older maps and techniques used at the time. A very common problem is not with the survey itself but with the datum used. Most modern numerical flow models are constructed with real world coordinate system

Uncertainty Source	Description
	reference and a defined projection (e.g. UTM, geographic). Natural resource sites often use local mine datum for their coordinate system ("mine grid"), which may be a rotated and/or scaled grid relative to the geographic or UTM grid, and/or with different elevation datum. There should be a final quality control done on water level data by the modeller. Position errors may be checked and corrected easily by rotating and scaling the old grid and old well coordinates if there is information about the geometry. It is not good practice to use head values as reported without some data quality checks by qualified modeller, unless the reported values are from another qualified modeller or hydrogeology professional who did the quality control already. • The modeller should also plot the relative locations of existing water level points (e.g. using GIS) to existing natural features or infrastructure, and check the position and elevation coordinates against the latest site maps. This map or table of coordinate values should be documented. • For all head observation points there should be a check of borehole collar elevations relative to new ground surface elevation model (DEM) and a correction of any systematic errors. All monitoring well collars should be very close to the ground surface model. Those which are not, should be investigated and corrected or not used in model calibration. This map or table of well collar elevation differences to DEM or differences between new and old survey results should be documented.
Monitoring piezometer design uncertainty:	Monitoring wells and piezometers have different screen lengths and have different quality of completion. Well screened over the entire aquifer respond differently in a heterogeneous aquifer than wells with shorter screens, depending on properties of aquifer around the screen. At some sites the slopes are unstable and wells may be blocked or cut off by slope movements over time, bringing into question the representativeness of previous measurements. Piezometers may also change over time their response to high frequency events due to screen clogging (e.g. grout leakage, geochemical processes, silting up). Usually, the long term response of the piezometer is not affected. In deep inclined holes, where pressure transducers are grouted in (e.g. vibrating wire piezometers), the absolute location of the sensor is important because the hydraulic head is calculated from sensor pressure and its position. Poorly surveyed boreholes which are strongly deviating may lead to large position errors of sensors. Its also not unusual to have sensor position error due to support pipe bending, simple counting errors during installation, and sensor loss of calibration (e.g. reporting wrong pressure). All of these uncertainties can increase uncertainty of a hydraulic head measurement in these types of installations.
Water level measurement error:	This type of error is associated with the water measuring device or the operator. Most modern pressure transducers can sense water pressure and level to within 0.1 mm or better, but some water levels are still taken with water level tapes and other methods, resulting in reading errors due to tape stretch, curving and sticking to walls of inclined borehole on the order of 0.5 cm to a few centimetres. There may also be rarely some problems with the automated measuring and recording device.
Data entry, unit conversion, and other database	The most accurate and representative data value may simply be incorrectly entered or transcribed somewhere in the analysis and reporting process, or the boreholes and positions of sampling zones in multilevel piezometers could be mixed up. This type of error is nearly impossible to trace if the modelling work relies on already published reports and existing

Uncertainty Source	Description
errors:	databases compiled by other workers. Some databases contain old and new data and may contain some errors. Typical problem may occur at sites where monitoring well labels and identification numbers have changed over the years, as this may lead to mixing up of borehole information (e.g. water level may be precise and correct but published for the wrong borehole location). Due diligence checking of particularly important monitoring points should be done if the water level does not easily fit in the conceptual model and numerical model results.

TABLE F2: Calibration Target Flux Data Quality Considerations

Uncertainty Source	Description
Assessment of discharge flux data quality	Groundwater flux is usually measured as groundwater discharge to surface water channels or to mine excavation. Hydrologic measurements of low flow (base flow) conditions give an approximation of groundwater discharge fluxes, especially in mountainous terrain where most of the groundwater discharges to the valleys. There are various techniques for streamflow hydrograph separation analysis if there are recurring runoff events (precipitation events). Groundwater flux to mine excavations can be obtained from dewatering statistics (pumping rates, pit lake level changes, mine water level changes, etc.) and will usually give a good estimate of groundwater inflow rates to such excavations. In water supply projects, the existing and past total pumping demand could be estimated with varying degree of confidence.
Sources of error in measured discharge data	• Representativeness of discharge measurements (locations of measurements) • Assumptions in hydrograph analysis (streamflow data) • Dewatering system statistics (e.g. from underground mine) or open pit water level changes (mine inflow); pumping demand statistics of an aquifer • Measurement method error (base flow measurement may be difficult if the streams receive continuous runoff from precipitation or ice melt) • Data entry, unit conversion, and other database errors
Assessment of recharge flux data quality	Recharge flux may be measured with infiltrometers, or estimated using a separate one dimensional soil column infiltration models such as HELP (ref…). At many mine sites, the water rock piles may be covered by other materials or synthetic covers, and the performance of these materials in limiting recharge may be uncertain, or it may change over time as a known function with time.
Sources of error in groundwater recharge data:	• Representativeness of recharge measurements (locations of measurements) • Assumptions in infiltration modelling (soil types, materials used as covers, geology, scale, precipitation inputs, climate, etc.) • Measurement method error (of direct measurements) • Data entry, unit conversion, and other database errors

TABLE F3: Calibration Target Salinity Data Quality Considerations

Uncertainty Source	**Description**
Assessment of water density (or salinity) data quality	In density-dependent flow models the water density measurements (salinity, Cl concentration, TDS, etc.) are used as calibration targets. The data is usually measured in monitoring wells through sampling and testing with field meters or laboratory, geophysical surveys of conductivity and other methods. Sources of error may include: • Uncertainty in well screen location or source of sampled water. • Measurement and data entry errors. • Temporal variation in water density and salinity (e.g. during active salt water intrusion in coastal aquifers, tides). • Misinterpretations of geophysical survey results. • Geochemical processes not accounted for.