



Guidelines for mine water management

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Executive summary

Mining influences the quality and quantity of water in the mine area and in its surroundings and changes hydrological and topographical conditions, sometimes drastically. According to the Finnish mine stress test study by Välisalo *et al.* (2014), water management is at the moment the most challenging stress factor in Finnish mines. In Finland, especially the problems with water balance management and large water quantities have lately been one of the main reasons causing environmental problems. The situation is similar also elsewhere, as in most parts of the world mining companies are exposed to some kind of risk related to the availability of water. Either there is a lack of water or the contrary, there is too much water. Both circumstances can cause significant effects on the mining operations and the environment. The lack of comprehensive and practical tools for efficient water management seems to be one of the main causes behind the problem, as can be seen from the following list which describes the current needs of mine water management that were identified in this report:

- Competence development and practical introduction of water management and modelling tools
- Improved (online) monitoring tools for data collection and organized data transfer
 - Both water quantity and quality are important for optimal collection, treatment and recycling of waters
- User-friendly water balance management tools
 - Quickly updatable, user-friendly interfaces
- Tools which enable integrating the water balances of different operations to one “site-wide-water-balance” taking into account both mine area and surrounding environment
 - How to overcome compatibility challenges between the different approaches used in planning?
- Integration of water balance management to process control system of the mine

A proper water management system can be beneficial to the mine. If the planning of water balance management actions has already been started in the early phases of the mine life cycle, several advantages can be gained. The reduction of risks and environmental impacts (e.g. preparation for extreme situations and changes of the water balance) is the most important asset, but early phase planning and data collection are also important when achieving cost and waste reductions as this enables an early phase modelling of the different scenarios and maximizes opportunities (Griffiths *et al.* 2008). Cost savings can be created, e.g. as a result of the use of optimum size storage capacity, diversion of different water types, and optimization of water-recycling activities. Good environmental performance also increases the social acceptance of the mine.

Water management is a continuous process that needs to be developed and updated throughout the whole mine life cycle, for example when changes in mining operations also affect the water balance. In the different phases of a mine's life cycle, the water management program will change. Even within a phase, as information and data are collected, knowledge increases and the need for revision and updating arises. As every site is unique, proper water management requires an understanding of the site-specific factors, and should always be applied case specifically. The use of a pro-active approach aiming to solve the causes behind problems beforehand instead of addressing symptoms is another key principle that should be followed when aiming for an efficient water management solution.

The mine water management system includes water balance modelling and water quality and quantity monitoring. The difference between water management and water balance is important. According to Mueller (2015), water management is a practical management structure with a strategy and goal that is often environmentally driven. Water balance is just one tool to achieve this goal (Mueller 2015). The design of the mine water management system should include forecasting and sufficient monitoring of hydrological conditions, adaptation to potential risk scenarios and collection of water quality data. The minimum requirements for monitoring and reporting are laid down in legislation and permits. Due to recent mine water balance management issues in Finland, the legislative requirements have become stricter, thus generating differences in requirements between "old" and "new" mines. Water balance management is also linked to waste management, as tailings ponds form a huge resource of contaminated mine water.

Nowadays it is still quite common that a spreadsheet-based deterministic approach (e.g. Microsoft Excel) is used for water balance modelling. With the help of specialized add-in tools (e.g. to assess uncertainties), a spreadsheet can even act as a dynamic modelling tool. Spreadsheets are useful for easy projections, and they can be rapidly implemented and used to store, display, and check dynamic model inputs, or display and analyze dynamic modelling results. However, they are not transparent, nor very well suited for complex modelling. Spreadsheet models may also be prone to errors. Thus, the shift from deterministic methods towards more versatile dynamic models that can be coupled to hydrological, geochemical, reactive transport and to chemical equilibrium models is needed. In certain countries, such as Canada, the USA and some European countries, a

dynamic approach is already commonly used in mine water balance modelling. The most well-known dynamic water balance simulator in mine water management is GoldSim. In addition to GoldSim, the dynamic simulators MATLAB Simulink, STELLA and Vensim are described in more detail in Section 5.2.2.2. In addition, the Watershed simulation and forecasting system WSFS is presented in this same context. The report also introduces the hydrogeological and groundwater flow models MODFLOW, MT3DMS, FEFLOW, MODFLOW SURFACT, HydroGeoSphere (HGS) and PHREEQC, as well as the equilibrium and chemical models HSC Sim, PHAST, PHREEQC, TOUGHREACT, HYDRUS 2D/3D, ChemSheet and OLI, in Sections 5.2.2.3 and 5.2.2.4.

A mine water quality and quantity monitoring program should encompass all the different types of waters in the mine area, namely process waters, natural waters (such as groundwaters and surface waters), as well as wastewaters and/or used waters (such as tailings and dams), and be dependent on the mine characteristics, surrounding grounds and waters, and other site specific factors. It is critical to monitor at least the water quality of outflow and discharge at sites downstream, but it is also advisable to study the water quality in the background and inside the mine site. Some common parameters monitored include temperature (T), pH, electrical conductivity (EC), redox potential (Eh), dissolved oxygen (DO), alkalinity, metals and metalloids, nitrogen and phosphorus compounds as well as other anions such as sulphate and chloride. The water monitoring should include the measurement of physico-chemical quality and water level, in parallel with local climate measurements. Surface water monitoring should also include flow measurements which are needed for water balance calculations. It is advisable to store all data from monitoring in a database with easy access. Having a dedicated weather station on site, whenever possible, is recommendable to gather accurate information and thus increase the reliability of the water management tools. Regular monitoring of surface and groundwaters and water levels combined with weather data is valuable for forecasting hydrological conditions and preparation for unexpected situations.

Monitoring can be performed online or offline. Nowadays, for example, the water flow, level, pH, T, EC, DO, turbidity, NO₃-N, and NH₄-N can be monitored online. The possibility to integrate the data from online monitoring to water balance modelling would be ideal. Continuous monitoring of water flow and water level in basins is recommended as good practice, however, regular visual inspections of basins are still important to confirm the operation of monitoring equipment and the water level in basins. Also the monitoring program should progress and develop over the mine life-cycle phases as more information on water sources, use, discharges, etc. is attained. The first water-monitoring step is taken when the environmental baseline study is performed before any alterations to the proposed mine area are made. Meteorological information on the prevailing conditions at the planned mine site should be collected for several years before mining activities and the monitoring program should be developed on the basis of critical assessment of this survey.

General guidance on how water management should be performed in the different phases of the mine life cycle is given in Section 6.4. Water management actions in the different phases of the mine's life cycle and the related permits are gathered in Table 5.

Chapter 7 summarizes the aims of a comprehensive water management program and gives the key points for setting up such a program in Finland. The chapter provides a brief overview of the evolution of the water management program in different phases of the mine life cycle. The infrastructure, techniques and technology are available to make the state of mine-site waters known to both mine operators and supervising officials. Speculations are also made as to how the management, software and monitoring will develop in the next decades.

Preface

This report aims to identify current and expected future needs for mine water management, to describe water management procedures and decisions in different phases of a mine's life cycle, to introduce good practices for water balance management, and present selected case study examples. Based on these, guidelines for mine water management are being created. This work is a part of the project "Management of water balance and quality in mining areas" (WaterSmart). The WaterSmart project is a part of the sustainable extractive industry program Green Mining by Tekes.

The WaterSmart project was co-funded by Tekes, Outotec Ltd, ÅF-Consult Ltd, EHP-Tekniikka Ltd, Boliden Kylylahti Ltd (formerly Kylylahti Copper Ltd), Yara Suomi Ltd, the Finnish Environment Institute (SYKE), VTT Technical Research Centre of Finland Ltd and the Geological Survey of Finland (GTK). The project was coordinated by SYKE.

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Contents

Executive summary	3
Preface	7
List of acronyms and computational codes	10
1. Introduction	14
2. Objectives	17
3. Water balance in mining	19
3.1 General aspects of water balance in mining	20
3.1.1 Water balance management system components	22
3.1.2 Different forms of water balance	23
3.1.3 Characteristics affecting mine water balance in Finland	25
3.2 Principles of good water management	27
4. Current status, needs and challenges	33
4.1 The Finnish stress test study	36
4.1.1 Objectives and background	36
4.1.2 Outcome of the study	37
4.2 Role of groundwater	42
4.3 Development of permit requirements	43
4.4 Monitoring	44
4.5 Modelling	45
5. Monitoring and modelling solutions	51
5.1 Water quality and quantity monitoring	51
5.1.1 Monitoring of groundwaters and surface waters	53
5.1.2 Monitoring of tailings ponds, seepage waters and dams	58
5.1.3 Monitoring sensors and analyses	59
5.1.4 Water quality and quantity data for water management	64
5.2 Modelling	65
5.2.1 Model development	65
5.2.2 Modelling software	68
5.3 Case examples	92

5.3.1	Comprehensive water management solutions	92
5.3.2	Equilibrium and chemical models.....	101
6.	Water management procedures.....	103
6.1	Mining legislation in Finland	103
6.1.1	Permits and procedures required by the Mining Act.....	104
6.1.2	Permits and procedures under environmental legislation	106
6.1.3	Other regulatory permits and procedures related to mine water management.....	108
6.1.4	Permit process scheduling	110
6.1.5	Responsibilities related to environmental safety	111
6.2	EU regulations behind the national legislation	113
6.3	Communication and community relations.....	117
6.4	Water management in the different phases of the mine cycle	120
6.4.1	Phase 1: Exploration, and pre-feasibility studies.....	120
6.4.2	Phase 2: Conceptual and feasibility studies	122
6.4.3	Phase 3: Mine-site planning	123
6.4.4	Phase 4: Construction and commissioning.....	124
6.4.5	Phase 5: Operation	124
6.4.6	Phase 6: Closure and after-care	125
7.	Guidelines and recommendations	128
7.1	General guides for setting up water management program in Finland.....	129
7.1.1	Steps to be taken in early phases	130
7.1.2	Water management after preliminary phases	133
7.1.3	Water management during site planning, construction and commissioning.....	134
7.1.4	Water management during mining operations	135
7.1.5	Water management after closure.....	135
7.2	Recommendations for the future	137
	References.....	142

Appendices

Appendix: Stress tests at Finnish mines

Abstract

Tiivistelmä

List of acronyms and computational codes

3D/4D ERT/IPT	3-dimensional/4-dimensional Electrical Resistance Tomography/Induced Polarization Tomography
AAS	Atomic adsorption spectrometry
AVI	Regional State Administrative Agency
BAT	Best available technique
BOD	Biological oxygen demand
CE	Capillary electrophoresis
ChemSheet	Thermochemical simulation program
CIL	Carbon-in-leach
Cl ⁻	Chloride
COD	Chemical oxygen demand
CoNi	Cobalt-nickel
Cp	Specific heat capacity
CPU	Central processing unit
ΔS	Change in storage
DLL	Dynamic link library
DO	Dissolved oxygen
DOC	Dissolved organic carbon
E	Evapotranspiration
EC	Electrical conductivity
Eh	Redox potential
EIA	Environmental impact assessment
EnKF	Ensemble Kalman Filter–method

ELY Centre	Centre for Economic Development, Transport and the Environment
EL methods	Mixed advection-dispersion problems
EQ3/6	Software package for geochemical modelling of aqueous systems
FD	Dispersion dominated problems
Fe ²⁺	Ferrous iron
FEFLOW	Finite element subsurface flow system
GoldSim	Monte Carlo simulation software
h	Hour or height
H	Enthalpy
HDPE	High density polyethylene
HGS	HydroGeoSphere model
HSC Sim	Process simulator based on the HSC Chemistry software
HST3D	Finite difference code
HYDRUS-1D	Modelling environment for analysis of water flow and solute transport in variably saturated porous media
HYDRUS 2D/3D	Software package for simulating water, heat, and solute transport in 2- and 3-dimensional variably saturated media
ICT	Information and communications technology
ICP-MS	Inductively coupled plasma mass spectrometry
IoT	Internet of Things (network of physical objects embedded with electronics, software, sensors and network connectivity that enables these objects to collect and exchange data)
MATLAB Simulink	Simulation and Link, an extension of MATLAB
MIKE 11	Modelling system for rivers and channels
MODFLOW	Modular three-dimensional finite-difference groundwater flow model
MODFLOW SURFACT	3D finite-difference flow and transport modelling code
MODPATH	Particle-tracking post-processing model for MODFLOW
MT3DMS	Modular three-dimensional multispecies transport model

N	Nitrogen
Natura 2000	Network of nature protection areas in the EU
NH-N ₄	Total ammonium NH ₄ ⁺ concentration
NO ₃ -N	Nitrate-nitrogen
ODE	Ordinary differential equation
OLI	Simulation software for electrolyte chemistry
P	Precipitation
PET	Potential evapotranspiration
pH	Acidity/basicity, $-\log[H^+]$, <i>i.e.</i> minus logarithm of hydrogen ion concentration
PHAST v.2	Simulates groundwater flow, solute transport, and multi-component geochemical reactions
PHREEQC	pH redox equilibrium (in C language)
q	Runoff
QAP	Quality assurance policy
S	Entropy
SMEs	Small and medium-sized enterprises
SO ₄ ²⁻	Sulphate
STELLA	Structural thinking experiential learning laboratory with animation software
T	Temperature
TDS	Total dissolved solids
TEM	Ministry of Employment and Economy
TN	Total nitrogen concentration
TOC	Total organic carbon
TOUGHREACT	Numerical simulation program for chemically reactive non-isothermal flows of multiphase fluids in porous and fractured media
TOUGH2	Models multiphase, non-isothermal fluid and heat flow, and multi-component transport in fractured porous media
TP	Total phosphor concentration
TSF	Tailings storage facility
TSS	Total suspended solids

Tukes	Finnish Safety and Chemicals Agency
TVD	Total-variation-diminishing
UZF1	Unsaturated-zone flow modelling package
Vensim	Simulation software for improving the performance of real systems
VSF	Variably-saturated flow package
WSFS	Watershed simulation and forecasting system

1. Introduction

Water is an extremely important resource for the mining industry. In fact, the availability of water is one of the major variables for the entire mining and minerals processing industry. The mining sector has many kinds of waters in its sphere of influence, and mining is a significant water user and producer of wastewater. Moreover, a mine site is also a part of a catchment area in a meteoric water circulation system with its surface and groundwater subsystems. (Salonen *et al.* 2014)

Water can also be a problematic resource for industry, as in most parts of the world mining companies are exposed to some kind of risk related to the availability of water. Either there is a lack of water or the contrary, there is too much water (Figure 1). Both circumstances can cause significant effects on the mine and its operations. (Buckley 2012)

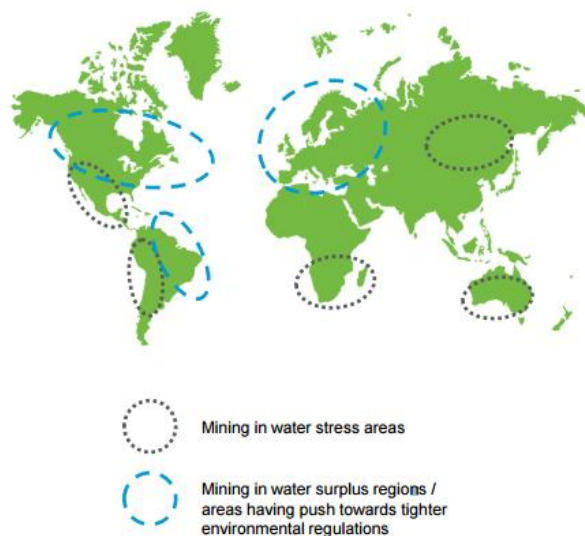


Figure 1. Mining and the availability of water (Kotiranta 2015, reprinted by permission).

Mining operations can have an influence on both the quantity and quality of water. Besides the changes in water quality, mining also changes the hydrological and topographical circumstances of the mining area. The changes in circumstances are sometimes significant and may cause effects on the surface runoff, groundwater behaviour, soil moisture content, and evapotranspiration. (Department of Water Affairs and Forestry 2008a) As every mine site has its unique properties, these aspects have to be carefully understood to be able to manage waters on the mine site and to avoid environmentally harmful effects. On the other hand, it is also possible to change the natural hydrological circumstances advisedly when aiming to improve water management in the mining area. For example, the size of the catchment area may be modified when aiming to prevent flooding in water surplus areas.

During recent years, the crucial role of water in mining has finally been recognized. Water cannot only be seen as an asset that creates value, but it is also a shared natural resource that needs to be carefully nurtured. (The Minerals Council of Australia 2014) The responsible use of water is becoming a critical business issue which affects the growth and profitability of mining companies. Although mining companies have long been conscious of water-related risks, they still face environmental problems. Facing these issues has proven how important it is for a mine to know its waters and to be able to manage its water balance. Inadequately assessed water management practices are one of the major concerns in the mining industry at the moment (Julien *et al.* 2005). In Finland, especially the problems with water balance management have lately been one of the main reasons causing environmental issues (Finnish Water Forum 2013). Particularly the management of large quantities of water has been problematic. These problems mainly emerge because the water balances of mine sites have not been adequately assessed in the planning phase of the mines. As a result, the permissions are based on inadequate information and the regulations of environmental permits have been difficult to implement in practice.

To meet the current and future demands for efficient water management, mining companies need to be increasingly conscious of the need for strategic planning of their water resources. Early strategic planning is crucial and not only leads to better security of different operations but also more effective investments in capital works can be attained. The costs of the early phase planning are low compared to the achievable cost savings and minimized risk in preventing damage caused, for example, by extreme weather events. Also sustainability drivers, e.g. energy consumption and social/environmental impacts are often included in the strategic planning. (Buckley 2012)

Water is often a protected resource and the risks related to surface and groundwater contamination caused by mining operations are in the public domain. Failures in water resource management throughout the whole mine life cycle lead to situations where community and government support for the current and forthcoming mining projects can be increasingly difficult to achieve. (Julien *et al.* 2005, Department of Water Affairs and Forestry 2008a) To be able to retain their social licence to operate, mining operations should closely evaluate their impacts on

quantities and qualities of water on both local and regional scales (IM Mining 2013).

The difficulties in mine water management indicate that more consistent and holistic approaches are required to help mining companies identify risks and opportunities related to the management of water resources. Not only is there a clear need for improved tools for handling water resources over the whole life cycle of a mine, but these tools should also permit the integration of different information types (Julien *et al.* 2005). For example, with the combined online water quantity and water quality measurements and mathematical models with predictive process control solutions, it is possible to efficiently manage the water balance and prevent flood situations, ensure water adequacy, and thus enable controlled mine water treatment. By determining how the monitoring and modelling tools can be integrated into the management system and process control in the most efficient way, an added value to the system can be created.

Background

- ✓ Water management is the most challenging stress factor at Finnish mines
- ✓ Mining influences the quality and quantity of waters in mine areas and in the surroundings, and changes hydrological and topographical circumstances of the area
- ✓ Effects on the surface runoff, groundwater behaviour, soil moisture content and evapotranspiration
- ✓ Sites are unique – proper water management requires understanding of the site-specific factors
- ✓ Water balance management and waste management are linked
- ✓ Minimum requirements on water balance monitoring and reporting are laid down in legislation and permits

2. Objectives

The management of water balance and quality in mining areas (WaterSmart) project aims to improve the awareness of actual quantities of water and water balances in mining areas to improve the forecasting and the management of the water volumes. One of the project goals is to exploit online water quantity and water quality monitoring for the better management of the water balances. The second aim is to develop mathematical models to calculate combined water balances including the surface waters, groundwaters and process waters as well as to test and develop the suitability of the models in the water balance calculations. The third aim is to determine how the monitoring and modelling tools can be integrated into the management system and process control. The WaterSmart project combines online measurements and mathematical models with predictive process control solutions where the objective is to manage the water balance and prevent flood situations, and on the other hand to ensure water adequacy and thus to enable controlled mine water treatment. A constantly updated management system for water balance including natural and process waters as well as mine de-watering and seepage waters is to be developed during the project.

This document provides background information for the project and describes the guidelines and related good practices for water management in different phases of mining therefore enabling selection of the most appropriate calculation models and measurements as well as control, reporting and decision-making practices. In more detail, the aim of this report is to:

- Describe current status, needs, and challenges of management of mine water balance especially in Finland
- Identify expected future needs for water management solutions
- Describe water management procedures and decisions in different phases of mine life cycle taking into account social aspects and legislation in Finland
- Introduce good practices for water balance management, especially taking into account:
 - Monitoring
 - Water balance modelling

- Integration of monitoring, modelling and process control
- Present examples of good water management actions implemented in practice

It is clear that better implementation of good practices in mine water management is needed to attain a responsible level of water use, treatment and recycling. These practices as well as experiences need to be collected to enable the development of the final mine-site water balance concept for possible commercialization, which is one of the project goals. Therefore, documentation of the created concepts, tools and work practices needs to be done. However, it should be noted that implementing various calculation models and measurements as well as control, reporting and decision-making practices at different sites may be challenging in practice because both operating and environmental contexts of each mine site are different. In addition, the know-how, data, and part of the modelling software are owned by various parties.

Better implementation of the good practices in mine water management is a necessity!

The main target group for this guideline report is the mining companies in Finland, which can utilize the outcomes of this report to support design and decision-making processes throughout the mine life cycle starting from early planning phases. The report can also be seen as a repository that can serve the needs of all relevant parties involved such as consultants, environmental administration, technology providers and research institutes. Due to the differences in operating environments across the mining sector and in different countries caused by, for example, differences in climate, national legislations, *etc.* it is hard to create a comprehensive guide that could be used internationally. However, there are common factors that can be reasonably well generalized and used as guiding principles for good water management even worldwide.

3. Water balance in mining

Water moves almost continuously in nature and is able to change its physical state under fluctuating conditions. The water balance equation obeys the principles of mass conservation in a closed system, which means that the water flowing into a certain area of interest over a specific time period must equal the water outflow, plus or minus a change of water storage within the same area. (Moriarty *et al.* 2007) (Figure 2)

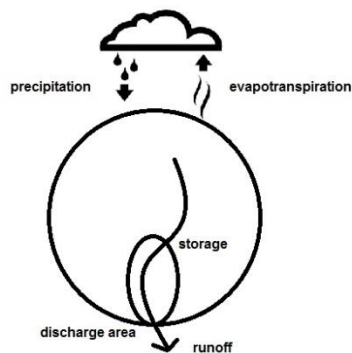


Figure 2. The basic components of water balance in the natural environment.

The water balance equation can be described as follows:

$$P = q + E + \Delta S \quad (1)$$

where

P = precipitation
q = runoff
E= evapotranspiration
 ΔS = the change in storage

3.1 General aspects of water balance in mining

To be economically feasible, a mine must be located in a place where the ore is deposited. Geographical location of the mine has a very big influence on the nature of water management. Hydrological and hydrogeological variables are among the most important factors affecting the water balance of a mine site. Feasibility of the mining operations depends greatly on adequate knowledge of the hydrological conditions of the area and the consideration of water-mining interactions (Agência Nacional de Águas 2013). Additionally, other site-specific factors have an important effect on water balance. Every mine site has its unique properties and these aspects have to be carefully understood to be able to manage waters within and around the mine site so as to avoid an occurrence of environmentally harmful issues (The Minerals Council of Australia 2014).

One of the biggest challenges for the mining industry is to ensure that an optimal amount of water is stored within the mine site to secure water availability for mining processes during droughts and, on the other hand, to be able to avoid unregulated discharges caused by flood periods. In an ideal situation, a mine would have just the right amount of water when it is needed. (CSIRO 2013) The efficient use of water resources can reduce risks related to water availability and also provide cost savings. The mining industry needs to have its water balance precise, dependable, and adaptive to scenario assessment when aiming for efficient water use and achieving these goals. (McPhail 2005)

To be able to sustain their operations, mines need to know how much water can be extracted or is discharged from the surrounding water resources (Vermeulen 2013). To put it very simply, mine water balancing aims to determine where the water comes from and where it goes or needs to be sent (McPhail 2005, Vermeulen 2013). Although in theory this may sound very straightforward, in practice the situation is usually more complex as water flows within the mining environment are multi-fold. A mine site is a part of the catchment area(s) in a meteoric water circulation system with its surface and groundwater subsystems; waters are precipitating, flowing, evaporating, infiltrating and accumulating within the site (Salonen *et al.* 2014). Mines exploit the local surface and groundwater resources by abstracting their service water either directly from the natural water resources (streams, rivers, *etc.*), dams, or boreholes, or indirectly from the water supply system (Department of Water Affairs and Forestry 2006a). As a mining company has many kinds of waters in its sphere of influence, such as waters from dewatering, process waters, wastewaters, seepage waters, and waters needed in material transport (slurry) and control systems (boilers, cooling systems) (Department of Water Affairs and Forestry 2006a, Salonen *et al.* 2014), it is very important for a mine to know its waters throughout the whole life cycle of the mine. For example, if the volume and composition of the different processes and the volume of fresh water flowing in every operating unit is known, mines become capable of optimizing water flows within the whole site and thus minimizing the use of fresh waters (Allen & York, *undated*).

Water balance management serves the interests of the mining industry when companies are designing their water management procedures and assessing their environmental performance, for example during environmental impact assessment and permit processes and during mine operation. An adequately accurate water balance compiled for different potential scenarios gives an opportunity for the mine to create a detailed plan for water management and thus also be able to prepare itself against unexpected changes. (Haanpää 2013)

Water balance analysis is a very useful tool when there is a need to determine, for example, the amounts of water formed in the operations, the contribution of waters derived from different sources eventually forming the recharge and discharge, the water available of the right quality to be used for mine processes, the deviations in water quantity, extra water needed, and seepage from the handling system to surface and groundwaters. The knowledge of water balance is also important in tailings management as, for example, the pond volumes and dam construction needs, discharge capacity of the ponds, and the need for a freeboard construction at the edge of the ponds can be assessed on the basis of the water balance in the area. In addition, the circulation and reuse of mine waters can be improved, and the need/capacity for water treatment and the handling of excess waters can be estimated on the basis of water balance data. (e.g. European Commission 2009, Agência Nacional de Águas 2013, Vermeulen 2013, Haanpää 2013)

Clear objectives should be defined for the whole life cycle of the mine when developing the mine water balance (Department of Water Affairs and Forestry 2006b). The water balance and water management options of the mine change and develop along with the different phases and also within each phase. For example, the water balance needs to be regularly updated during the operational phase of the mine (Haanpää 2013) to ensure that there is a sufficient amount of water available for the processes and, on the other hand, to prevent spillages. This requires constant monitoring and measuring. In addition, the earlier in the mine life cycle the designing has started, the more efficient and cost-effective the results will be (Agência Nacional de Águas 2013). Designing the water balance already in the early phase of the project may be challenging, because knowledge of water circulation, environmental requirements, or water balances of the unit processes may not be specifically known at that time. However, it may also offer several possibilities, e.g. water balance can be adaptable to different scenarios. (Haanpää 2013)

Depending on the purpose and mine life cycle phase, water balance information can be monthly or annually generated or specifically produced for a certain period (e.g. for spring runoff period) (Haanpää 2013). Some of the information needed (such as the climate data) can be gathered from public sources, but the rest needs to be collected using field measurements.

3.1.1 Water balance management system components

A comprehensive water (balance) management system encompasses all of the waters and water cycles on a mine site as well as waters affected by the mine site as building blocks linked to each other (Figure 3). In general, the mine-site water cycles can be divided into three categories:

- Process waters flowing in the plant and the process effluent waters to be discharged after treatment.
- Natural waters that include groundwaters, surface waters, as well as rainfall, snowfall and water evaporation; this is the category of clean waters. Mine dewatering waters basically represent groundwaters but due to their possible salinity, high concentrations of metals and metalloids as well as the amount of N-compounds, water treatment is usually required.
- Tailings, dams, ponds, seepage waters *etc.* encompassing wastewaters and/or used waters that may or may not need treatment; here is also included the treatment facilities.

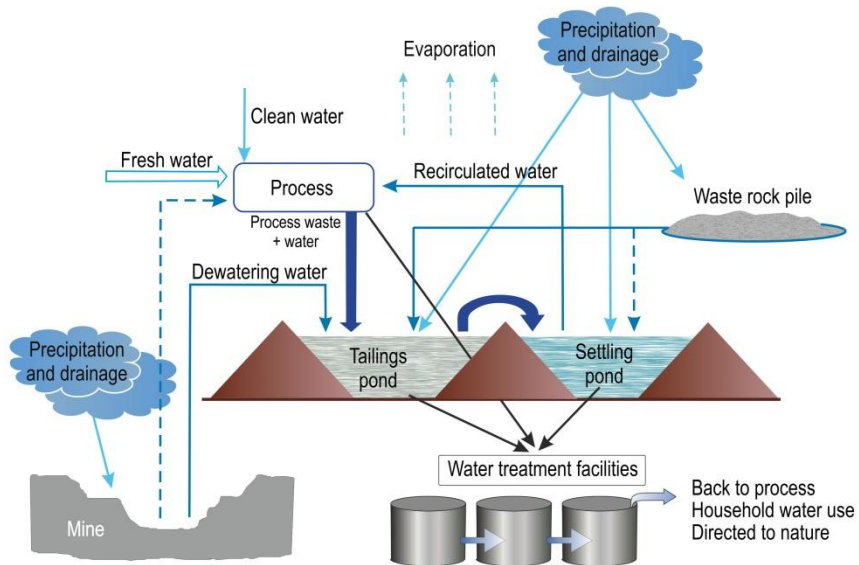


Figure 3. Example of different mine water sources and streams (modified from Kauppila *et al.* 2011).

Process plant water cycles and monitoring are at the core of the economy of the mining company. As the plant is an enclosed area, the monitoring and data collection in the plant is centred on its infrastructure and is a part of the process operations. During the mine-planning phase, the plant water requirements are stated.

The plant process operations will also set the amount of wastewaters leaving the plant. These are the two key points that link the plant and the surrounding mine site and its water systems.

Natural waters on the mine site and those in the surroundings form the second main category of waters. These waters are needed as fresh water supply for the process plant, or may be diverted from the site if not contaminated. The other main focus of these natural waters is their state and quality as waters are discharged from the mine site into the surroundings. The flow routes of the groundwater and surface water may also change as the mining operations and the wastewater systems are operated.

The third category of waters is those that can be called the waste and treated waters of the mining operations. The mining operation will result in different qualities of wastewaters and, if unfortunate, some accidental spillages or leakages may occur, causing problems to the natural waters and the environment. Seepage may also damage the structural integrity of the tailings dam. These accidents may be caused by, for example, ruptures in the pipelines, overflowing of undersized tailings storage facility, or seepage through the tailings pond embankments. (Water and Rivers Commission 2000)

The category of wastewaters/treated waters is the most diverse and therefore calls for extensive attention. The various qualities of waters have to be designated and the need for treatment assessed. It is vitally important to keep clean waters, potable waters, and different kinds of wastewaters in their own cycles and not to mix treated reusable water with wastewaters that require more extensive treatment. This is a major area where cost savings can be made. On the other hand, the treatment and reuse of waters on the mine site will require more of the water monitoring system. The quality of the waters to be recycled will have certain requirements that have to be carefully monitored.

Setting up a water balance management system that incorporates different quality waters at the mine site will result in a comprehensive program covering also the water processes that occur outside the plant in the ground, in the catchment, to and from the environment, and so on. The system will monitor and allow control of the waters and thus be an integral part of the mine-site's process control system.

3.1.2 Different forms of water balance

Water data accounting can be seen as a preliminary stage of water balance. The mining companies should measure and record at least those flows that need to be reported under the terms of their licence conditions. Flows are often measured periodically, but online measurements are more informative and thus recommended. The recorded data is stored within a spreadsheet and it enables producing trend graphs and making comparisons against different important parameters, such as supply limitations and operating targets. However, as this kind of data collection does not give the possibility of evaluating opportunities to improve water use efficiency and water management, it is therefore necessary to generate a

follow-up, or a so-called basic balance, which takes into account all inflows, discharges, and losses (such as precipitation, evaporation, wastewater runoffs, surface and groundwater inflows and outflows, water intake, discharges and seepages) across a specific operating unit within the mine water circuit and calculates the unknown flow as the balancing one. If this is done across different operating units, the unmeasured flows can be determined, which further raises the value of information in the balance (Figure 4). The accuracy of different flow measurement components defines the accuracy of the balance. (McPhail 2005)

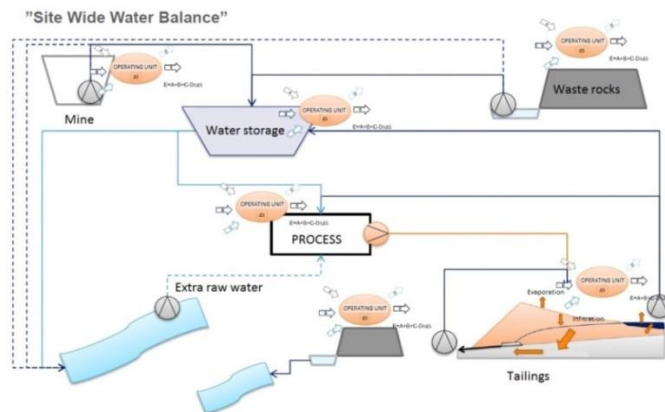
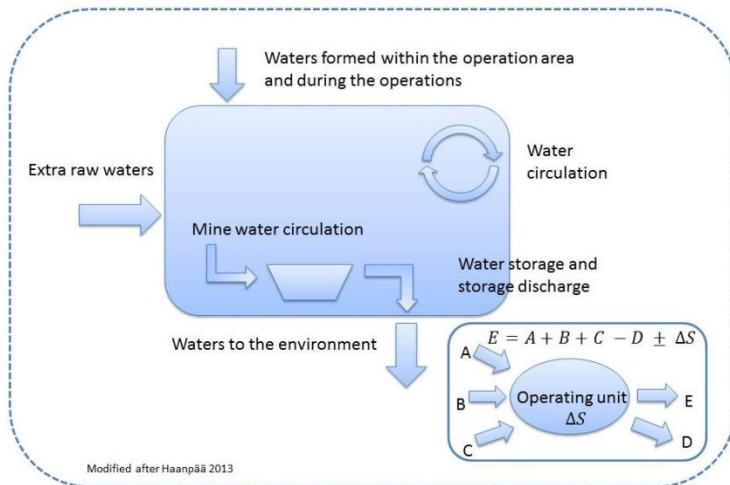


Figure 4. Site-wide water balance with its different operating units (modified from Haanpää 2013).

A site-wide water balance integrates individual balances across different operating units into one model. It consists of the whole operation area of the mine and all of its functions, including mineral-processing operations if they are present at the

site. Both fresh and wastewaters are included, as well as the amounts of waters formed during processing, in quarrying, dewatering, and waste rock disposal, in the tailings, soils and ores, not to mention the waters in ponds. (Haanpää 2013) (Figure 4) In addition, it should be noticed that there are also diversion waters within the mine site that are actively managed but not used. These waters flow from an input to an output, but are neither stored with the thought of being used or treated later, nor utilized by the operational facility. (The Minerals Council of Australia 2014)

A basic water balance is a useful tool in identifying those actions that are the biggest water users and losers in the whole mining circuit. Also, it is possible to conclude variations in water flows by analyzing the data gathered in the course of time. By adding control logic measurements (such as level sensors and supplementary storage capacities) into the water balance, it is possible to get even more out of it. The incorporation of a control logic system allows making predictions and leads from a basic balance option to water balance modelling. (McPhail 2005)

Deterministic predictive water balance modelling enables the inclusion of potential management changes with associated control logic variations/additions and helps in modelling the potential efficiency of these actions (McPhail 2005). For feasibility studies, it may be enough if simple deterministic simulations are performed monthly or yearly, but as the project progresses to the next phases, more complex models are required with the capability to perform stochastic simulations (Janowicz 2011). In Section 5.2.2.1 an overview of some of the most well-known deterministic modelling approaches currently in use is presented.

The most sophisticated type of water balance is the so-called probabilistic predictive balance or dynamic balance. Dynamic modelling is a useful tool when aiming to solve the behaviour of a certain system over time, and it may also provide valuable information when studying systems that have feedback loops as well as oscillating systems (Maest *et al.* 2005). The basics of dynamic modelling and the software most commonly used are further described in Sections 4.5 and 5.2.2.2.

3.1.3 Characteristics affecting mine water balance in Finland

Finland is located in the northern hemisphere, between the 60th and 70th northern parallels. Finland is a part of the Eurasian continent's coastal zone, with characteristics of both maritime and continental climates. Rainfall in Finland is moderate around the year. (Finnish Meteorological Institute 2014) Based on the data of precipitation, runoff, and evaporation it can be seen that the availability of water is not a problem for the mining companies located in Finland (Table 1). In Finnish mines, the water balances are usually net positive (Haanpää 2013). According to Salonen *et al.* (2014), the typical overbalance varies from 40% to 60%.

Table 1. Average amounts of precipitation, runoff, and evaporation in Finland (Karhu 2005).

	Amount, mm/a	Comments
Precipitation	500–750	August is the most rainy, March the driest
Overall runoff	200–400	Share of spring runoff is around 30–50%
Evaporation	300–400	In Northern Finland the evaporation rate is only ~25–50% of the average

Winters in Finland are cold and wet, but the weather can change rapidly (Finnish Meteorological Institute 2014). Temperature, snow situation, freezing of water systems, fast melting period, and the depth of ice are all strongly connected to water balances in Finnish mines. The temporal variations in precipitation and melting periods as well as cold temperatures may complicate mining operations. In cold climates, frost may freeze waters during the cold winter periods, thus making the use of water resources impossible for the mine. Freezing of water supply system pipelines may also lead to failures of critical processes. (ICMM 2012) In addition, the seasonal changes, e.g. the hydrological years and their division into dry and wet periods can affect the water balance (Department of Water Affairs and Forestry 2006b) and should be taken into account.

The increasing trend of global warming is predicted to continue in the future and is expected to have greater impacts on hydrological systems, resulting in more vulnerable water resources (IPCC 2007). The increase in mean temperature and precipitation in the northern countries, including Finland, would also increase the mean annual runoff. In Finland, no statistically significant changes in mean annual discharge or annual maximum discharge are seen, in general. There are, however, clear trends in the seasonal discharge series with increases in winter and spring mean discharges, and earlier timing of the spring peak in many of the observation stations (Korhonen & Kuusisto 2010). The increase in precipitation and surface runoff will cause more storm waters to accumulate in the mining area.

It is important to remember that water resources can be unevenly divided even in a humid climate. In Finland, around half of the rainfall infiltrates into the ground, but regional conditions, such as the hydraulic conductivity in soil and bedrock, the amount and duration of rainfall, the forms and slopes of the land, vegetation, and different surfaces affect infiltration rates. A part of the infiltrated water turns into the groundwater; the ratio can be up to 50 % in coarse glaciofluvial soils, *i.e.* sands and gravels. These regional aspects are, however, usually known during the project planning phase and thus the main uncertainties that may affect the water balance are usually related to the amount of dewatering waters from mine pits and the water balances across tailings areas. (Haanpää 2013)

In recently glaciated terrains, such as in Finland, the complexity of the Quaternary strata can vary from simple to extremely complicated. In Finnish mining areas the bedrock is typically fractured and takes part in groundwater flow and the transport of potentially harmful substances. The depth and the shape of the mine pit, together with the hydraulic conductivity of soil and bedrock affect the amount

of dewatering waters formed within the pit. Knowledge of fractures and joint zones helps in determining the need of dewatering and in protecting groundwater and surface water contamination. (Haanpää 2013)

Other regional variables include soil and groundwater conditions and the mutual location of the different functions (Haanpää 2013). Volumes and flow rates of groundwaters located in the area have an effect on mine water sufficiency. The characteristics of the aquifers, such as transmissivity, size of fractures, hydraulic charge and thickness of protective layers influence mine water availability (Agência Nacional de Águas 2013) and the risk of water contamination.

3.2 Principles of good water management

Ensuring the sustainability of mining processes in the long term requires responsible mine water management, which is one of the most important challenges within the mining industry at the moment. Decision-making authorities around the world are also focusing on improving the performance of current management procedures. It is important to understand the difference between water management and water balance. According to Mueller (2015), water management is not the same as water balance, but a practical management structure with a strategy and goal that is often environmentally driven. Water balance is just one tool to achieve this goal.

In the past it was common that water management issues were either completely disregarded or a reactive approach was used, aiming to comply with regulations by focusing on finding remedies to problems that had already occurred. A reactive approach is usually more expensive, less efficient and not as sustainable as a pro-active approach, where water management is integrated into the mine planning phase and water management actions will start early during the mine planning. The environmental effects can be minimized more easily and at minimal costs, because the causes behind the problems are addressed instead of symptoms. A pro-active approach is based on the use of adequate environmental and hydrological data and it also requires continuous data collection, collaboration with regulating agencies, and extensive planning. (Sawatsky *et al.* 1998)

An optimal water management solution for a mine site encompasses water balance models and water quality and quantity monitoring data relevant to the phase in hand. All waters connected to the operations are perceived in the optimal solution. Thorough planning and development of precise mine water management with a holistic approach is a contributory factor leading towards successful mining (State of Victoria, Department of Primary Industries 2014). Water management needs to be planned separately for each mine site, and cover the whole mine life cycle. Site-specific standards, ambitions, operational procedures and contingency plans are developed in the water management plan for legislative requirements, risk management, monitoring of hydrological processes, operations and emergencies, water quality and supply, erosion, computer models, performance indicators, as well as research and training (Environment Australia 2002, cited in European

Commission 2009). It is important to use qualified personnel in modelling, technical studies and design of different activities. Good co-operation among partners, designers, operators, and regulators is required. In addition, public participation of interested and affected parties, communities, stakeholders, and authorities helps to gain acceptance for the project. (Department of Water Affairs and Forestry 2008c)

Mine water management system designing is very important, but it is just as important to be able to successfully operate or modify the generated system. The capability to forecast the behaviour of the water management system using dynamic and probabilistic methods is a must in the modern mining industry which requires a good understanding of system feedbacks with local hydrologic circumstances and the ability to use pro-active measures to maintain normal operation. Early planning of water management and fluent adjustment to changing conditions are both greatly dependent on comprehension of the water balance of the area. Appropriate monitoring and close collaboration between different functions within the site are required for achieving successful site water management. (Shelp *et al.* 2009)

Temporal variations in water quantity and quality and their impacts on surface and groundwater systems must be defined quantitatively and qualitatively currently and in the future. In addition, the cumulative impacts of each individual aspect of the mining operation within the site must be assessed. The objectives and targets for water management need to be continuously reviewed based on new data and accordingly updated frequently to achieve continual improvements. (Department of Water Affairs and Forestry 2008c)

Because of many uncertainty factors related to mine planning, both operational conditions and real-life mine site, water management systems can be very different from what was planned during the mine design and development phase Table 2). Solving the causes behind the uncertainties helps mine operators to modify the processes and create a new operational procedure. However, water management systems can be quite complicated, and the use of water balance modelling is often required to assist the decision-making process. The uncertainties behind real-life mine site water management systems may be caused, for example, by changes to the mine plan, waste rock and tailings characteristics, and mine process water qualities. Operators must customize either the operational rules or physical structures of the water management systems to be able to adjust to these changes. (Shelp *et al.* 2009)

Table 2. Uncertainty factors and their causes related to operational conditions (Shelp *et al.* 2009).

Uncertainty factor	Cause
Overestimation/underestimation of the amount of site rainfall, or pond evaporation	Lack of meteorological data during the mine design
Variation of process water reclaim rates	Unforeseen long-term mine waste behaviour
Change in water consumption rates	Mine plan modification

To reach the goals of good water management, it is important that hydrological and hydrogeological conditions of the mine site's catchment area such as ground-water tables and interactions between surface waters and groundwaters are known, that water quantity and quality are monitored and managed, and that water management structures and techniques are chosen in a way that they are durable and can easily be maintained. However, as operational, environmental and social factors related to mining are unique for each mine site, an unambiguous procedure for efficient water management in mining is not easily created (ICMM 2012).

The goals of water management differ, for instance, in different climates. In dry areas mine water management focuses on reusing and recycling as much water as possible and on reducing water losses. On the other hand in humid areas, it is essential to have, *e.g.* an adequately scaled water storage, diversion systems to separate fresh and process waters, and constructions to prevent landslides or liquefaction caused by tailings releases. (Lindholm 2014) However, one aspect is applicable to all mines; the basic objective of water management is to protect water resources in a way that water quality, quantity, and aquatic ecosystems will remain as pristine as possible. To reach this goal a three-step decision-taking hierarchy based on a precautionary approach should be followed, in the following order of priority; the first step requires pollution prevention, the second one underlines impact minimization, and finally, if these two actions are not applicable, the last step focuses on the effective and responsible discharge or disposal of wastewaters. (Department of Water Affairs and Forestry 2008b) (Figure 5)

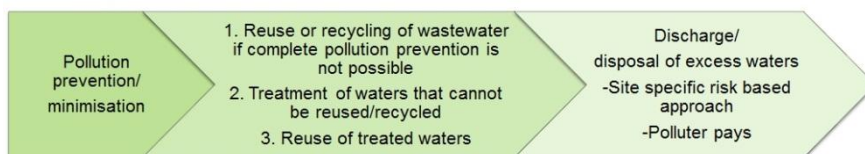


Figure 5. A hierarchy of decision-taking (Department of Water Affairs and Forestry 2006a–b, 2008a–c).

The following list of actions is collected to back up the basic principles of water management (*e.g.* Water and Rivers Commission 2000, Department of Water Affairs and Forestry 2008a–c, Janowicz 2011, ICMM 2012, State of Victoria, Department of Primary Industries 2014, Allen & York, *undated*):

Pollution prevention, control of water flows

- Water balance model needs reliable and accurate measurements of the quantity and flow of water within the mine site for verification.
- Water pollution should be prevented both inside and outside of the site.
- Reuse and recycle waters as much as possible to minimize water consumption and to avoid water discharges into the environment.
- All actions within the whole life cycle of mining should be performed in a way that it would disturb the surrounding natural hydrological and hydrogeological water systems as little as possible.
- Different water types should be kept and managed separately to diminish unnecessary water quality deterioration, and the amount of water that needs to be treated or retained.
- To avoid contamination, the access of fresh water to the mine site should be kept at the minimum.
- Clean excess waters should be diverted around or away from a mine site and/or vulnerable facilities into natural water systems.
- Other mine-site runoff should be diverted around or away from any vulnerable facility to on-site storage areas, such as a sedimentation basins or retention basins.
- Quality and quantity of effluents must be ensured not to cause harmful impacts on the surrounding environment and other water users.
- Wastewater disposal is allowed only if the receiving environment is able to assimilate additional waste and discharge water loads.
- Regional impacts and interactions regarding surface and groundwater systems between adjacent mines and other local activities should be studied.
- Erosion in a mine site should be controlled, e.g. by vegetation to prevent drifting of the sediment that may cause water quality deterioration in the receiving water systems.
- “Polluter pays” principle should be obeyed.

Unexpected situations

- Storm water management is essential to control discharges associated with mine activities and runoff, and to minimize the potential for dams containing toxic chemicals to overflow, or for runoff to carry suspended solids to natural water systems. Storm water management at the mine site should provide for the collection, storage, and disposal of water.
- Any storm water diversion should be properly managed to prevent erosion and downstream sedimentation. Flow diversion is usually best achieved by building a bank from soil excavated from the channel.

- Water management and treatment systems should withstand extreme water flows and quality changes. For example, the vulnerable facilities such as hazardous material stores, power stations, fuel storages, and waste stores should be built above the level of extreme flood events.
- Water management should not be planned on the basis of yearly average amounts of rainfall, but to cope with exceptionally high rainfalls. Data from continuous monitoring of rainfall and snowmelt during the previous years may be a better basis for the water management program than yearly averages.
- Risk assessment of possible leakages or seepage water from tailings storage facilities minimizes the risk of environmental problems.
- Management measures must be implemented to minimize or mitigate the observed risks. The more inclusively the risk assessment is made, the lesser it has to be changed and updated in the course of the time.
- Availability of sufficient water for processes should be assured.

Infrastructure

- If possible, the mine infrastructure should be located in a way that minimizes possible effects on the water system.
- Design, manage and maintain efficient infrastructure for collection and conveyance of various water streams or sources on the mine site.
- Water storages such as reservoirs and ponds should be firm and broad enough to handle expected water volumes and to meet the legal requirements.
- The facilities that generate waste materials or wastewaters should be roofed or covered to prevent rainfall mixing with waste products.

Acid mine drainage

- To avoid the formation of acid mine drainage and other negative effects of dissolution, the contact time between ore and water should be as short as possible.

Underground mining

- In underground mines, the water interchange and transfer between the surface and underground should be kept at the minimum level.
- Dewatering of the underground mine inhibits water contamination.

Mine closure

- Water management actions should be designed to take into account mine closure requirements and risks related to it to secure that closure objectives are not compromised. Closure considerations for water management should ensure that all long-term residual impacts on water quality are recognized and properly managed.

- The knowledge of water movement in underground mine cavities should be taken into account in closure planning.
- The mine is responsible for the environmental impacts as long as impacts are observed. Financial provisions for water management measures should be made during the life cycle of the mine to reach the objectives of the closure and beyond.
- Rehabilitation must also be done during the mine operation to minimize final rehabilitation needs.

4. Current status, needs and challenges

Many operators within the industry already have their own frameworks for monitoring, measuring and reporting their water use, but these frameworks may be very complex, take into consideration only part of the site impacts, and are not often consistent across different operations, companies, and other sectors of water reporting. These are usually the main reasons why communication with stakeholders as well as comparison between sites and across different sectors can be very challenging. Usually, however, the information recorded by different operators is quite similar, and to be able to promote its consistency, a better structured and more consistent approach for producing information about the water resources is needed. (The Minerals Council of Australia 2014)

A more consistent approach also requires that the water cycle of a mine site is interconnected with the general hydrologic water cycle. Therefore, reliable, real-time data on the amounts of water is needed, in particular during water-rich seasons with heavy rain and snow melt events but also during harsh winters when water freezes and is not available for use. In areas of water stress, the challenge is the opposite; sustainable water resource management is required to enable significant reductions in water use. In addition to knowledge of hydrological conditions, the control of the water balance in the mining processes requires knowledge from unit operations of ore beneficiation, the ability to adjust process parameters to variable hydrological conditions (integration of control of mine water balance to the process control system of the mine), adaptation of suitable water management tools and models, as well as systematic monitoring of quantity and quality of water. Moreover, recommendations are needed for designing large enough capacity for water management infrastructure to handle the variable water volumes and separate different mine waters as well as to assess the pollutant loading, dispersion, mixing and dilution in receiving water bodies.

Currently, there are no comprehensive water balance models available that could allow stakeholders to sustainably manage mine-site water resources, carry out risk analyses, evaluate and predict potential environmental impacts, optimize site operations or support strategic planning of mine-site operations. The information needed is scattered and site-dependent, and it is therefore difficult for authorities and the mining operators to utilize the data. The main problem with the existing models is that the water cycle of a mine site is not thoroughly intercon-

nected with the general hydrologic water cycle. Although the scientific knowledge required for site-wide water balance modelling exists, the practical problem is that the required monitoring systems, application knowhow, calculation models as well as ICT tools required to transfer data and generate and visualize mine-site water balance have been scattered amongst various operators. Therefore, there are compatibility challenges and the practical ability to manage, forecast, and control mine site-wide water balance is suboptimal. Typically, collecting the relevant information is very labour intensive and requires experienced professionals from various organizations to tackle the four problems presented below:

- **Data sources:** There are a very limited number of players capable of providing reliable monitoring solutions to enable real-time visibility of water quantity and quality data.
- **Modelling:** Modelling expertise related to various environmental and process water sources exist but these capabilities are usually owned by different stakeholders and cannot easily be accessed by the parties having the required input data. Selection of appropriate models is also difficult since the operating and environmental context of each mine site is different, water sources and water availability between mine sites vary, and catchment areas as well as groundwater sources differ by geology, topography, etc.
- **Collaboration:** Although the knowledge required for mine-site water balance modelling is globally dispersed by the various stakeholders in extensive meetings and seminars, they only disseminate the broad lines of knowledge. The specific details required for calculations are stored in geographically local and small groups of people, therefore lacking transparency. Collecting the necessary pieces of information requires a lot of collaboration as well as time, skill, and motivation. Often this is not achieved and therefore stakeholders do not have a complete picture of mine site-wide water balance. (In Finland, general natural water balance over the whole country is relatively easy to get for areas 1–10 km² and larger. The water balance is simulated with WSFS [Watershed Simulation and Forecasting System], and all data is stored in one place.)
- **Deployment:** Implementing various measurements and calculation models as well as control, reporting and decision-making practices into different mine sites is challenging because both the operating and environmental context of each mine site is different. In addition, the involvement of several stakeholders as well as the share of their responsibilities becomes confusing.

In 2013, the Ministry of Employment and Economy (TEM) released an action plan called “*Making Finland a leader in sustainable extractive industry*”, which includes, for example, proposals for the development of operational environment of the extractive industry to obtain society’s support. The report highlights the need for better management of water balance in mining. The central efforts in water management should focus on endeavouring towards closed circulation of process waters, decentralized water treatment and systematic evaluation and monitoring of

effects on water systems. To be able to achieve these goals, water management plans for mines are needed in addition to development of water technologies. This means that existing mines should perform “a water review” in which the water balance, consisting of the use of rainwater as well as other waters, drainage, treatment and recycling, are determined. In addition, more attention to the water management actions should be taken as early as during the planning phase. Water balance is the starting point in generating a water management plan that will also consist of follow-up monitoring of water balance and updates of the model. The aim is to keep different kinds of waters apart and to have a closed circulation for process waters. The investment in developing the water technologies can mean, for example, developing dynamic water balance models for the needs of the companies. (Ministry of Employment and Economy 2013)

The Finnish Water Forum (2013) has commented on the action plan TEM released. In their comments, the Finnish Water Forum pointed out that of the recent issues facing the Finnish mining industry, managing water balance in the mines has been one of the most important environmental challenges facing the industry. According to their view, the reason is not so much in the lack of know-how but rather choosing, investing and correctly applying the appropriate management program. The Finnish Water Forum also emphasizes that the aims for closed circulation of process waters, decentralized water treatment, and systematic evaluation and monitoring of effects on water systems are important development and investment targets. They also endorse the suggestion to create mine water management plans and develop water technologies. The Finnish Water Forum encourages mining companies and parties responsible for public funding to act according to the suggestions. This would allow achieving a real understanding of the mine’s water balance, and evaluating and managing the risks therein. These aspects would create cost savings in the long term. (Finnish Water Forum 2013)

The following sections of this chapter aim to describe more closely the current status, needs and challenges of mine water balance management of Finnish mines:

- The description of the current status is presented in Section 4.1, and is based on the results of the stress tests enquiry by Välisalo *et al.* (2014) implemented in 2013. The stress test results also reveal some needs and challenges of the current management of mine water balance.
- As groundwaters are often poorly observed and managed in mine water management even today, their role is separately underlined in Section 4.2.
- Due to recent challenges in mine water management, permit requirements have become stricter. Thus, Section 4.3 presents some examples of the environmental and water permit decisions and their permit requirements from recent years.
- The status, needs and challenges especially concerning monitoring and modelling, and experiences of the modelling experts, are separately discussed in Sections 4.4 and 4.5.

4.1 The Finnish stress test study

4.1.1 Objectives and background

After the waste-water leak in Talvivaara mine in Sotkamo, Finland, in November 2012, the Finnish government decided to carry out stress tests for the Finnish mines. The recently published results from the mine stress test study ("*Kaivosten stressitestit 2013*") by Välisalo *et al.* (2014) reflect the current status, needs and challenges of the mine water balance management of Finnish mines, although the aim of the original study was to clarify how mines have prepared themselves (*e.g.* company's readiness and strategies) for unexpected situations that may cause environmental risks. In this first phase of the testing, the stress tests were outlined to cover different kinds of emergency cases that may occur in the mining processes. The study also aimed to improve risk management and find good procedures and practices which could further be used in other mines and other industrial sectors where applicable. (Välisalo *et al.* 2014)

Unexpected situations in mines can result, *e.g.* from defects in storage and tailings ponds' dam structures or foundations originating from the mine planning and construction phases, from workmanship, or from extreme hydrological phenomena (precipitation, meltwaters). Failures in the enrichment process, equipment failures in the wastewater process, overflows, and sudden floodings in wastewater discharge ditches may cause disturbances in mine water management. Waste sludges may overflow into the environment by partially the same token or, for example, due to dam collapse. Furthermore, accidents, power failures, and vandalism may lead to unexpected situations. To be able to map such situations occurring in the Finnish mines exceptional situations at mines were studied as a part of the stress test development. As a result of this account, 128 emergencies in Finnish mines were recognized between 2006 and 2012. About half of these (68 cases) were connected to water (Figure 6). Most water-related situations were caused by water and waste treatment, or more generally, water management and concentration activities. Typical situations included, for example, dam leakages, overfilling of the ponds, small accidents and failures, pipe breakages, and failures in hydrometallurgical or concentration processes. In most of these cases, the mine operators generated a follow-up plan in co-operation with authorities to fix the situation. (Välisalo *et al.* 2014)

Stress test questions were sent to every metal mine and concentration mill currently operating in Finland. In addition, industrial mineral mines and carbonate mines having classified waste dams or water dams or that handle chemicals on a large scale were tested. The near proximity of sensitive targets (*e.g.* groundwater areas, surface water intake areas, population, nature conservation areas) also affected selection of the mines. (Välisalo *et al.* 2014)

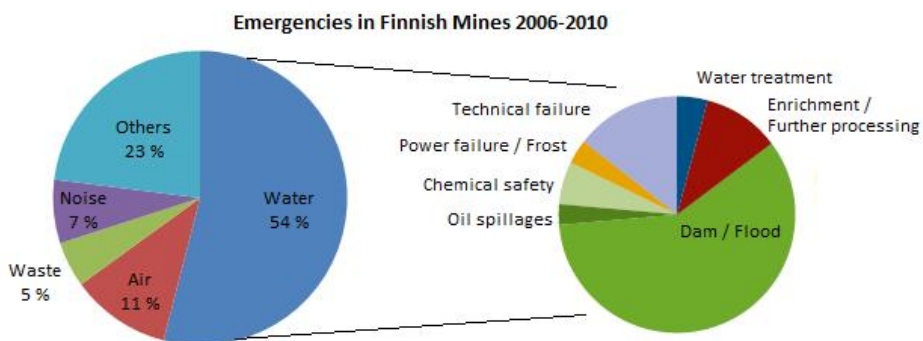


Figure 6. Emergencies in Finnish mines 2006-2012 (n=128) and especially water-related cases (n=68) (Modified from Välisalo *et al.* 2014).

The general questions sent to the mining companies as a part of the enquiry were related, for example, to the water balance of the mine, structure of the reservoirs, and situations identified as probable causes of danger to the environment. The questions were steered to describe the operational system of the mine. The following information concerning water balance was gathered from each mine to get a good picture of each case (Välisalo *et al.* 2014):

- Schematic diagram of the water balance of the site; water balance management methods of the mine.
- Maximum capacities of the ponds (amount of free water), reserve capacity under normal conditions and estimate of their adequacy under problematic situations, expected operating lifetime of the basins. (Välisalo *et al.* 2014)

After the general questions, altogether seven risk cases concerning water management and foreseeing of management needs, monitoring and repairing the condition of storage and tailings dams, detection of the spreading of detrimental substances, evaluation of the seriousness of the situation, and reporting were analyzed in more detail. After the self-evaluation phase of the mines, a group of specialists analyzed the answers. (Välisalo *et al.* 2014)

4.1.2 Outcome of the study

The stress test study was concerned with provisions for exceptionally high precipitation and runoff that are known to cause problems for water management, water storage, and water discharge. Based on the answers, the expert group suggests that at least older mines should check the hydrological sizing of the dams. The sizing should be done in such a way that the basin is large enough to contain the reservoir water without the need to release any water from the pond to the surroundings. (Välisalo *et al.* 2014)

Decanting equipment is closely related to the management of flood waters. No answers were given to question number one that concerned the operation of these devices or possible risk concerning dam failures. (Välisalo *et al.* 2014)

The surface areas of mine dam constructions are small compared to their runoff areas in natural water systems, and thus the effect of flash floods may become a sizing factor. Based on the answers, only two mines acknowledge the effect of flash floods in sizing their capacity. Whether the storage capacity of the basins was adequate was not unambiguously clear in all of the answers. (Välisalo *et al.* 2014)

The monitoring of hydrological conditions (Risk 1; question 1 in the study) in Finnish mines differs drastically depending on the mine. For example, while some mines reported that they perform only visual inspections, others reported that they perform hydrological monitoring by doing water level and water volume follow-ups, dam condition checks, groundwater monitoring as well as follow weather conditions and weather statistics. A few mines also collect data on the amount of snow, the water content of snow and its effect on water balance, and increase monitoring frequency of the basins during melting periods and exceptional rainfalls. Some mines have online monitoring capacity for flow measuring from discharged waters or are using other means for monitoring the amounts of pumped waters. (Välisalo *et al.* 2014)

It is also important to be able to forecast hydrological conditions. All mines observe the amount of water in the basins either by doing visual inspections or by measuring water levels. The development of the basin situation can be assessed based on the results from regular monitoring, which helps in preparing for unexpected changes. The level of awareness can be raised further if online sensors are used for measuring the amount of water leaving the basins. Continuous monitoring enables faster reactions to the changes in water flow. Some mines already use this kind of monitoring technique. The recommendations based on the answers of the stress test underlines the need for continuous flow monitoring. However, the use of online monitors does not eliminate the importance of regular basin inspections. The operation of automated monitoring equipment and the amount of water in the basins need to be confirmed by actual site visits. (Välisalo *et al.* 2014)

Forecasting water quantities should be based on real observations of the dependency between weather conditions and flowrates, not only on theoretical calculations. Forecasting the impact of hydrological conditions is accomplished by using weather forecasts, hydrological forecasts and weather observations. Hydrological forecasts take into account the snow situation and water content of the snow. It would be essential to know the catchment of the mine with enough accuracy to enable finalizing the water balance and keeping its different units under control. Weather stations in the mine area generate a lot of local statistics and if the amount of precipitation is known, the amount of “fresh” rainwater accumulating in waste areas and diluting waters can be calculated. (Välisalo *et al.* 2014)

Although most mines probably perform regular monitoring of surface waters and groundwaters and observe water levels via observation wells installed in dams, these were not mentioned in the answers. This data should be connected to the

weather statistics so that it would be possible to recognize the possible consequences of different situations and also to be able to predict them in the future. Additionally, if pumping capacities were added to this examination, the possible effects of power failures would be revealed. (Välisalo *et al.* 2014)

Question number two (Risk 1; question 2 in the study) asked how the mines are prepared for hydrological extreme situations (exceptionally high precipitation on a yearly or monthly basis, spring flood, or exceptionally heavy rain) and what their planned precautionary measures are (treatment, storage, discharges). The amount of precipitation and melting waters in the Finnish mines is usually high. Furthermore, waters accumulate at mine sites from other parts of the catchment. Therefore, water discharging is needed. Emission quality control requires assurance that the quality of the waters being discharged is good during normal operation as well as under exceptional circumstances. If necessary, waters should be treated before discharge. Overfilling of basins and the associated risks should be prevented and clean runoff waters directed past the dam basins thus decreasing the filling of the basins and the amount of waters that need treatment. Some mining companies use ditches for directing clean waters to prevent overfilling. (Välisalo *et al.* 2014)

Good practices used in the Finnish mines

- ✓ High recycling rate for process waters
- ✓ Fresh discharge waters are kept away from process waters and dewatering waters
- ✓ Generous spare capacity and water treatment capacity

The purpose of reserve basins is to avoid the need to discharge untreated mine waters out of the mining area in the case of an emergency. The reserve basin capacity should be large enough such that discharging excess waters into water systems during unexpected situations (*e.g.* floods) is not the only way to manage large amounts of waters. Before the waters are discharged into water systems, the possibility of discharging these waters into mine pits should be investigated, as they can be used as temporary storages. The answers by the mines as to the means for managing hydrological risks showed that many operators do not currently have reserve basins and thus direct water discharges are the only option to manage excess waters in basins. Some mines have included these extra discharges in the discharge amounts filed for in their water and environmental permits, while others rely on applying for an extra permit for the excess discharges if such a situation arises. The use of mine pits as reserve basins was not revealed in these answers, nor was how the environment would withstand the additional load caused by extra discharging. In addition, it should be noticed that having the water in reserve basins is not meant to be a permanent solution, but there needs to be capacity for treating and discharging waters from the mining area. (Välisalo *et al.* 2014)

An alternative solution would be to build a sufficient reserve capacity for the existing basins. In many cases, however, there were already studies and ongoing plans to build new reserve basins, while at the same time some answers stated that there was not necessarily enough space available on the mine site for constructing these basins. If unplanned water discharging is the only possible option, water quality measurements should be made to confirm that no unnecessary loadings to the underlying water systems occur, and if necessary, be prepared to treat the waters. As permit regulations usually restrict discharges, unexpected situations should be brought forward and dealt with as far as possible already during the permit process phase of the environmental and water permit. The knowledge of water quality during the discharges and the possible effects of the quality issues on the underlying waters are items that were not evident in the answers. (Välisalo *et al.* 2014)

Good practices for monitoring hydrological conditions used in the Finnish mines

- ✓ Own weather stations
- ✓ Online monitors for measuring water flow leaving the basins
- ✓ Water balance models that can be quickly updated
- ✓ Integration of weather data with water balance to be able to forecast changes
- ✓ Automatic measurement of water level in basins

The requirement to install process-like water treatment systems should be included when granting permits to new mines. The process in a water treatment plant can be adjusted according to different situations. Discharging fresh water outside of the mining area is not the problem, but rather the impurities that the mine waters contain. A process tailor-made for treating waters that will be discharged from the site enables adjustment of the water treatment capacity according to the variations in the amounts of waters. Therefore it would be unnecessary to store water in the mining area and thus the discharging of detrimental elements to the surrounding environment is prevented. Emission limits should be based on concentrations of detrimental elements (including salt ions) as well as total amounts. This would allow releasing larger amounts of waters from the mining area if the concentrations are below limiting values, the water treatment is sufficient, and there is no harm to the environment. (Välisalo *et al.* 2014)

Water quality treatment plants that can be adjusted according to the amount of water to be treated are seldom used in the mining industry. Water treatment is almost exclusively based on gravitational sedimentation in large basins. As the amount of water increases, stream velocities increase, and thus sedimentation may weaken if the retention time of water in the basin is not long enough before it is discharged. pH is the most important variable in the treatment of metalliferous waters. When the pH increases, metals precipitate in the basins. Because natural waters are inherently more or less acidic in Finland, discharged waters should not be too alkaline. In some cases, the sedimentation of solids is intensified by using chemical coagulants. If water treatment is based on the pH regulation, continuous pH monitoring is needed. In the future, to improve water treatment, the use of

actual water treatment plants should be considered especially in relation to their effects on the quality of discharge water and on the environment. (Välisalo *et al.* 2014)

The monitoring results from longer time periods should be critically assessed to be able to develop the content of different monitoring programs (such as dam monitoring program, water management monitoring program in mine waste areas, environmental monitoring program) especially regarding environmental loadings and impact assessment. The focus should be put on observing whether measures of the monitoring program help in recognizing possible failures (for example, failures in water treatment, seepages from waste areas, management of excess waters, load peaks caused by sudden changes in weather conditions). The monitoring should be revised when the need arises, for example, if the chemical quality of the seepage water changes. This part of the documentation systems should be improved and it would be important, for example, to create a database, in which monitoring results from different operations could be reviewed with a user-friendly interface. Those mines that treat and release environmentally harmful waters should have their own laboratories to be able to quickly recognize and react to possible changes in water quality. Furthermore, this makes the planning and implementation of monitoring much easier. (Välisalo *et al.* 2014)

Recommendations based on the stress tests

- ✓ Continuous flow monitoring should be used, if possible. The results need to be confirmed by regular basin inspections
- ✓ Forecast the impact of hydrological conditions based on regular monitoring of surface and groundwaters and water levels combined with weather data
- ✓ Direct clean runoff waters past the dam basins
- ✓ Ensure sufficient reserve basin capacity, *e.g.* by investigating possibilities to use mine pits as reserve basins or to build more reserve capacity to existing basins
- ✓ The unexpected water situations should be dealt already in permitting process
- ✓ Discharge limits should be based both on concentrations and total amounts
- ✓ Process-like water treatment systems should be installed in new mines
- ✓ Develop the monitoring programs based on critical assessment of monitoring results from longer time periods
- ✓ Revise the monitoring program when the need arises
- ✓ Create a database with user-friendly interface where different monitoring results can be reviewed

The self-evaluation comments by the different mines and the feedback from the expert group given on the basis of the self-evaluation are briefly described in Appendix. On the whole, even though the mines seem to be fairly well prepared for unexpected situations, water management has to be revised and the detection and management of high loadings improved. Mine water management is the single most challenging factor in the stress tolerance of Finnish mines. (Välisalo *et al.* 2014)

4.2 Role of groundwater

Groundwater is an important freshwater resource for drinking-water supply and mining uses. It plays an essential role in the hydrological cycle and is critical for maintaining wetlands and river flows. It also provides a base flow to surface water systems. Mining activities have impacts on the groundwater behaviour, as mining changes the natural condition of groundwater systems and may also weaken groundwater quality. For example as a result of pit dewatering, the groundwater table declines within an aquifer (Salonen *et al.* 2014) and contact with freshly exposed rock material reduces the quality. Also the partial removal of the aquifer during excavation increases the vulnerability of the aquifer to be polluted. Moreover, mining can increase the water pathway or permeability around the mine wall due to extensional fracturing induced by blasting (Younger 2004), which results in more groundwater flow into the mine pit. On the other hand, the added rock pressure to quarry walls can reduce the flow. Mining may have even wider scale consequences on groundwater than the mining companies have assessed, as the geometry and hydraulic conditions of groundwater reservoirs are usually not well known. Therefore, it is important to understand the groundwater flow system and its characteristics in each mine site, the change of groundwater storage, the interactions between the groundwater and surface water, as well as the water balance of the watershed area. (Salonen *et al.* 2014)

Mine groundwater management practices try to prevent or minimize degradation of groundwater quality and quantity caused by the mining activities. The occurrence of deposits, groundwater accumulation and discharge (Salonen *et al.* 2014), groundwater uses, mine operations and facilities, and ecosystem are all critical to the sustainable management of water resources in the mining area and need to be considered and addressed in the water resources and management. It is also necessary to establish a dewatering plan from the beginning of the mine life cycle, *i.e.*, from the mine pre-feasibility phase through to the mine closure and after-care. This plan should include the collection of groundwater baseline data, groundwater monitoring, and/or groundwater modelling in different mine sequences and development phases.

Mining companies should recognize the importance of groundwaters and start managing them better. Their meaning is usually not well acknowledged or assessed in mining districts (Salonen *et al.* 2014), as can be seen from the previous answers of the stress test. Although groundwater studies should be performed already at the early mine planning phase before any alterations to the planned mine area are made, this is seldom the case in spite of recommendations given in many guidelines published during the recent years (Salonen *et al.* 2014). Also in the later phases of the mine life cycle, groundwaters are often poorly observed and managed and even nowadays a reactive approach is commonly used. However, the situation may change in future. The Finnish Environment Institute released the Groundwater Studies Check List at the end of 2014 to enhance groundwater protection, to prevent groundwater contamination and ease groundwater risk management. It is further described in Section 5.1.1.1.

4.3 Development of permit requirements

Mining is regulated by many acts and degrees, and mining activity requires several permits. The requirements set (for example, the minimal requirements for water management) in the permit decisions for different mines vary because the influences of mining differ according to the geology of the site, the type of mine, and the processes used as well as the sensitivity of the environment around the mine. During recent years, the permit requirements have become stricter, thus generating differences in requirements between “old” and “new” mines. Three examples of the environmental and water permit decisions and their permit requirements from recent years are presented below:

- The requirements for water balance management in Kittilä gold mine described in permit decision (No. 72/2013/1) set the need for the separation of clean and contaminated waters (clean waters can be discharged to the ground or to water systems, while other waters must be treated before leading them to the surface irrigation field or back to the mine water circulation), and regulated the directive maximum flow rates for treated process waters. Additionally, the permit decision set the requirements for the qualities of the different water types. (Regional State Administrative Agency 2013)
- The environmental and water permit decision and permission to start activity in Rämepuro mine (No. 36/2014/1) define the requirements for collection, treatment, and discharging of dewatering waters, seepage waters and runoff waters, and effluents into the water. According to the decision, clean waters can be discharged to the natural water system without treatment. The amount and quality of these waters are to be monitored on demand. A detailed construction plan is required for water collection, treatment and discharging, which should also contain a provisional plan for unexpected situations (spare basin capacity). In addition, requirements were set for the quality of the waters discharged from the treatment process for the dewatering waters. (Regional State Administrative Agency 2014a)
- Talvivaara mine is a unique mine in Finland as its processes differ from all other Finnish mines. The permit requirements for Talvivaara in the partially approved environmental and water permit decision (No. 36/2014/1) are much stricter than the requirements set in the two aforementioned permits. For example, on the basis of the monitoring plans from the year 2013, Talvivaara has to implement an intensive inspection program in its water management and water balance development. The mine is also required to ascertain that the leaching process is functioning. The mine is required to report the results on a monthly basis to Kainuu ELY-Centre. The mine also has to draw up a detailed management and treatment plan for safety waters, drainage waters and seepage waters. (Regional State Administrative Agency 2014b)

In addition, the general pollution prevention requirements in Kittilä's and Talvivaara's permits require that control and surveillance systems for the produc-

tion processes, water control and treatment are to be developed to generate real time information for the licence holder. This information allows assessment of whether the mine operation complies with the environmental protection criteria set by the permit. (Regional State Administrative Agency 2013, 2014b) The strict requirements for Talvivaara are set as a consequence of recent environmental problems and violation of licence conditions caused by the mine as the water management in the mine area has been extremely challenging due to high water overbalance. Furthermore, the effect of the large size of the mine can be seen in the requirements. Altogether, the situation in Talvivaara has increased the general awareness of mine water management issues in Finland.

Moreover, Kittilä mine has just recently suffered from water management problems that have been widely reported in the media. Dam seepage occurred in the mine in September 2015 and caused uncontrolled discharge into the environment. To be able to remediate the situation, the water level in the pond needed to be reduced and thus a special permit to discharge the additional volume of water was requested and approved. (Agnico Eagle Finland Ltd. 2015)

4.4 Monitoring

Monitored water quantity and quality data can be linked to the water balance model either as online or imported data that then relays the information to the operators or directly to the process control system of the mine. To be able to react quickly to perturbations in the water cycle systems, online monitoring is needed. During recent years, much effort in Finland has been focused on developing new methods for obtaining information on our water resources (Huttula *et al.* 2009, Lepistö *et al.* 2010). Special emphasis has been put on the development of reliable methods and technologies capable of providing real-time information on water quality and flow rates. Currently, only few parameters can be linked to the water balance model and they mainly give data on water quantity. However, the use of real-time measurements for water monitoring is increasing. These capabilities to measure natural water-related phenomena and water flow rates also in challenging environments form the solid foundation for innovating new practices for controlling mine-site water balance.

Water quality is determined from a combination of field measurements and laboratory analyses, which are used as tracers for weathering processes that generate contaminant fluxes in the real environment. An online monitoring system (*i.e.* a sensor network) helps detect the changes in physical characteristics and an immediate sampling and analysis can be undertaken and possible intervention procedures started to prevent adverse effects (Heikkinen *et al.* 2008). Sampling and monitoring sites are selected on the grounds of hydrogeological and sedimentological characters of the site to estimate the pathways of the contaminants. It is critical to monitor at least the water quality of outflow and discharge sites downstream, but it is also advisable to study the water quality in the background and inside the mine site.

Monitoring of water balances is currently conducted with online or offline precipitation, evaporation, discharge and groundwater level measurements. The precipitation and evaporation measurements are usually taken using a weather station, but the discharges and groundwater levels are often measured manually. However, the use of online monitoring of mine water discharges and pressure sensors in groundwater observation pipes and on weirs are becoming more frequent as more detailed information is needed for management of the mine water balance. Online monitoring of mine water quality of recycled water fraction as well as discharges to recipient waters are also becoming more common in Finland. The major difficulty in online monitoring has been freezing during winter, the proper design of the monitoring equipment for variable water volumes as well as difficulties in calibrating water quality sensors. Thus, there is a need for sensor development and better quality sensors. Improving the quality of online water measuring is a big economic and technological challenge, which, if successful, would be extremely beneficial to the water management system. The proper selection of measured physico-chemical parameters for water quality monitoring is also challenging. A knowledge of chemical reactions and reactive substances in the water are key factors in selecting the parameters for quality monitoring. Monitoring of electrical conductivity from saline and metal-containing mine water discharges is common. Also important are the pH, Eh, DO and turbidity monitoring that describe the acidification, metal solubility and reactivity, amount of suspended solids and risks of water toxicity as well as oxygen demand.

Water quality is dependent on various parameters and it is advisable to characterize the total chemical composition of waters, including cations and anions as well as organic contaminants. The total chemical composition of water allows the fluctuations in water chemistry related to mining activities to be pinpointed. Thus, the water samples are analyzed at least for total and soluble metal and metalloid concentrations and anions. For more comprehensive study, it is advisable to determine also both total organic carbon (TOC) and dissolved organic carbon (DOC), ferrous iron (Fe^{2+}) (Heikkinen *et al.* 2008, Kauppila *et al.* 2011), total dissolved solids (TDS), total suspended solids (TSS), sulphate (SO_4^{2-}), and chloride (Cl^-) since they are often significant for the estimation of water quality.

Unfortunately, in many cases monitoring is still performed only at the minimum level to fulfil the permit requirements, although a more comprehensive monitoring program would offer better protection against unexpected changes. It should be also kept in mind that manual sampling and laboratory analyses may not be fast enough in these kinds of situations.

4.5 Modelling

Water management relies on the accurate data fed to the water balance modelling program. The modelling solution should be able to predict and explain the trends in the parameters and to relate the condition of the waters on the mine site. It will also be used to make risk and sensitivity analyses of the process and water sys-

tem. These analyses will show the mine operators those segments of the process system that are the most susceptible to fluctuations and how the water balance system reacts to extreme conditions. The risk analysis will show which points in the water system would cause the greatest damage in case of malfunction or a catastrophe. This information will allow the operator to compile safety instructions and have maintenance operations ready when accidents occur.

Deterministic models (such as spreadsheets) are commonly used for analyzing basic water balances within mine sites. However, these approaches are not able to handle the occurrence of transient and probabilistic events (Julien *et al.* 2005) and suffer from a lack of transparency as well as limited flexibility to model complex systems and long time periods (e.g. Haanpää 2013). Therefore, the use of general purpose dynamic simulators is more advisable when simulating and evaluating the performance of more detailed mine water management systems and should be preferred, even though dynamic models can sometimes be troublesome to evaluate or replicate due to their potential complexity and lack of standardized model development procedures (Maest *et al.* 2005).

GoldSim, probably at least partially due to its flexibility, is perhaps the most common dynamic software used in mine water balance calculations internationally. Nevertheless, although dynamic models have been around for a while, they have not been widely used in mine water management yet (Griffiths *et al.* 2008). In Finland too, the situation is similar; the results of the Finnish stress study described in Section 4.1 revealed that regional water balance modelling is not a standard procedure in Finnish mines, except in a few/one cases (Talvivaara) with WSFS.

Recent developments in dynamic system modelling allow traceable and transparent integration and assessment (for example: a player version for end-users without a licence requirement in GoldSim, client-specific user interfaces and control panels) of all the factors and processes (*i.e.* water balance components) that may impact water management. This creates several benefits compared to deterministic modelling. A dynamic system approach offers a quantitative tool to evaluate the performance of the system and to test the logic of each mining sub-activity. Dynamic water balance calculations should include all those processes of the mine-site components where the water quantity and/or quality can change during different life cycle phases of the mining project. The calculations can be also extended, defined and edited for the various planning and operational needs of different life cycle phases. Databases and spreadsheets can be linked or integrated dynamically into the overall simulations, meaning that the effects of input-changes can be simulated on the fly. Also external programs like mineral process simulators, reactive, hydrochemical transport models, 3D surface, seepage and groundwater flow models, *etc.* can be integrated into the system platform and into the overall dynamic calculations. Mass balances of water quality as well as the geochemical transport and reactions in variably saturated porous media can be included in dynamic system modelling. The model will then show the water mass balance for the mine site during the full cycle of the mine and year round including surplus and water deficiency spans. It is also possible for mines to program their

own process modules such as climate generators, detailed waste pile and tailings structures and processes, and that way produce mine-specific software with client-specific user interfaces and control panels.

Monitoring information can be combined with water balance modelling in the dynamic system approach. The use of common modelling and monitoring environment enables continuous updating of model predictions and parameters always when new measurements are available (data assimilation). It is also possible to carry out multitask optimizations and with weather forecasts produce, for example, flow forecasts. Data assimilation is an optimal approach to combine observations into water balance calculations. Historical time series are commonly incorporated into model calibration when combining monitoring data in the modelling. Real time "data driven" modelling based on data assimilation, however, gives an opportunity to further calibrate the model, but the model is updated with monitoring data that enables model development and produces more precise forecasts. "Data driven" modelling is carried out using the Ensemble Kalman Filter (EnKF) method and stochastic simulation of predictive realizations (dynamic calibration for time-series results in a set of parameter values that is time dependent). EnKF can produce continuous updating of model predictions and parameters always when new measurements are available. The deviation between the model output and the measured data is reduced over the monitoring period. It is possible to integrate EnKF into any simulator, such as the GoldSim platform using its stochastic tools. EnKF process produces automatically also uncertainty and sensitivity information. WSFS also has an automatic updating system for water balance simulation and forecasting purposes.

With dynamic system modelling, it is possible to predict future behaviour, identify which factors have the greatest influence, answer "What-if?" questions, and evaluate alternatives (also through an optimization process). Uncertainty and sensitivity analysis can be performed using the Monte Carlo tools. Models such as GoldSim, STELLA, Vensim MATLAB Simulink, and WSFS allow the naturally occurring integration of different variables with their respective variability functions. This kind of approach is especially good when modelling the system's sensitivity to extreme events or its behaviour against the changes in the treatment system that can cause progressive drifting of some variable, such as water quality (Julien *et al.* 2005). Uncertainty and risk analyses give valuable information to the mine operator on the sectors of the mine site that are apt to be under stress if the conditions become unfavourable. The mine operator can then make preparations in case these extreme conditions become reality.

Variability can be either caused by a random event or sporadic operating conditions, whereas uncertainties may arise from the estimation accuracy of different water balance parameters. For example rainfall, rate and area of evaporation (especially the pond in the tailings storage facility), production rate, ore type, equipment malfunction, and maintenance timetable can cause variabilities in the mining environment. Uncertainties include coefficients of rainfall runoff, together with seepages, lock-up water volumes, and evaporation rates from wet/damp beaches related to the tailings storage facilities. The tailings storage facility with its

associated infrastructures is usually the operating unit that causes most variability and uncertainty. Around 80% of water circulation is connected with the tailings facility and the tailings storage operations also cause the largest losses in the mine water circuit. On that account, achieving the right water balance for tailings storage facilities is an extremely important factor when aiming to achieve the right water balance for the whole mining area. (McPhail 2005) More uncertainties exist in the excess water sources, especially in dry climates. Water supply is commonly the main area of uncertainty in modelling, particularly if a remarkable contribution can be obtained from underground or open pit dewatering processes. (Griffiths *et al.* 2008) Other things to consider include the final solids content of the tailings after consolidation caused by tailings disposal and the actual moment when water gets separated from the tailings (Haanpää 2013). Also the forecasting of evaporation is one of the challenges in modelling.

In Finland, sudden changes in weather conditions such as exceptionally heavy rains and rapid snow melting may cause challenges for mine water management. For example, the effect of water level rise caused by spring melt is apparent in some open pits and thus the consideration of melt waters is important in water balance modelling. The possibility of these kinds of extreme situations was not identified in the older permit requirements, and thus the size scale of the water infrastructure may be insufficient to tolerate sudden water loads. In Finland most of the water management is based on calculations of precipitation, evaporation and runoff, which can only give a broad view of water quantities. In old mining sites the water management is usually based on experience. This approach relies on single or few key personnel and the transfer of information may be difficult. Also the adjustment to water management and actions in acute situations cannot be tested in advance as in the water management modelling approach.

Groundwater modelling can be a useful tool for aquifer characterizations and predictions of groundwater flow path, future drawdowns from pumping wells, and interaction with surface water bodies. Predicting future water reductions through modelling may be necessary where the hydrogeology is complex (*i.e.*, multiple aquifer or fracture flow systems) or in groundwater limited/critical areas that are sensitive to the withdrawal of groundwater or water level changes due to mine dewatering over time. This information can be used to determine the appropriate depth and lateral extent of the mine, and the mining sequence. In addition, the model results will indicate the potential impacts on the natural groundwater or surface water sources. Modelling is a predictive tool that can benefit the operator by allowing the maximum resource extraction to occur while preserving the groundwater level around the mining area in the original condition. In addition, it can be used in the public hearing process to address concerns about the potential effects from dewatering operations (EALW 2010).

Dynamic modelling helps/is needed to, e.g. (e.g. Julien *et al.* 2005, Department of Water Affairs and Forestry 2006b, Griffiths *et al.* 2008, European Commission 2009, Agência Nacional de Águas 2013, CSIRO 2013, Haanpää 2013, Vermeulen 2013, Allen & York, *undated*)

Sustainably manage mine-site water resources

- ✓ Determine the volume and effect of every water component within and around the site
- ✓ Compare between raw water needs and available resources
- ✓ Estimate water treatment needs
- ✓ Identify and mitigate water losses, and thus reduce raw water extraction
- ✓ Observe how much water can be extracted or is discharged from the surrounding water resources
- ✓ Recognize and quantify the contribution of waters derived from different sources

Carry out risk analyses (sensitivity, uncertainty and variability)

- ✓ Provide for extreme events and unexpected changes (e.g. exceptional weather)
- ✓ Perform stochastic simulations
- ✓ Evaluate system sensitivity behaviour against the changes in the treatment system
- ✓ Predict future behaviour and factors having greatest influence on water balance
- ✓ Assess different potential scenarios

Evaluate and predict potential environmental impacts

- ✓ Make environmental licence applications
- ✓ Assess environmental performance
- ✓ Prevent unregulated discharges

Optimize site operations

- ✓ Determine internal factors of the system, e.g. process and plant water requirements
- ✓ Optimize water flows within the whole site and thus minimize the use of fresh waters
- ✓ Minimize waste amounts
- ✓ Assess tailings pond volumes and dam construction needs, discharge capacity of the ponds, and the need for a freeboard construction
- ✓ Minimize costs
- ✓ Improve circulation and reuse of mine waters
- ✓ Estimate need/capacity for water treatment and handling of excess waters
- ✓ Determine deviations in water quantity
- ✓ Assess process water availability during dry seasons

Support strategic planning of mine-site operations

- ✓ Define objectives for the whole mine life cycle
- ✓ Perform an early phase modelling of the different scenarios
- ✓ Maximize opportunities
- ✓ Create efficiency
- ✓ Create detailed water management plan

The current methods for forecasting groundwater flow directions and velocities vary from simple hydraulic head interpretation to mathematical groundwater flow and transport modelling. As the complexity of the Quaternary strata can vary drastically in Finland, the simplest methods cannot be applied in every case and groundwater flow and transport modelling are needed. In addition, it is typical that the bedrock is fractured and takes part in groundwater flow and the transport of potentially harmful substances. Therefore, a need for a hydrogeological model or a model of the geological structure that takes into account the hydrogeological conditions in both soft sediments and bedrock is crucial to the understanding and modelling of the groundwater flow in mining areas.

The tools for hydrogeological modelling and groundwater flow modelling are commercially available. Solving the mathematical equations for the groundwater flow is automated, whereas the modelling of the geological units, *i.e.* the geometry of the flow model, and the parameterization can be difficult and requires many geological, geophysical and hydrogeological studies and measurements. Commercial groundwater modelling packages usually have extensions for, *e.g.*, the calculation of the flow in unsaturated, partially saturated or in frozen media, forward and backward particle tracking and calibration. The geometrically accurate and correctly calibrated groundwater flow model can be used to predict the temporal evolution of the groundwater flow and balance in the mining area. Also, changing the geometry and parameterization is very useful when evaluating the groundwater effects, *e.g.* of the earth-moving and building in the mining area.

The groundwater flow model can be coupled or used in conjunction with the reactive, multicomponent, geochemical modelling software (*e.g.* geochemical programs PHREEQC and EQ3/6 or reactive transport models, such as TOUGHREACT, HYDRUS 2D/3D and PHAST) to model the reactive transport of the groundwater. This approach helps to minimize the adverse effects of contaminants transported with the groundwater. Models are capable of simulating thermo-hydro-geochemical processes, but the possibility to observe geotechnical and mechanical aspects is usually lacking, which is a challenge. Groundwater flow, transport and reactive modelling combined into a comprehensive surface water flow model with linking of results both ways gives the water management personnel in mines an invaluable tool for water management.

Current needs

- ✓ Competence development and practical introduction of water management and modelling tools
- ✓ Real-time information
- ✓ Improved (online) monitoring tools for data collection
 - ✓ Both water quantity and quality important for optimal collection, treatment and recycling of waters
- ✓ User-friendly water balance management tools
 - ✓ Quickly updatable, user-friendly interfaces
- ✓ Tools which enable integrating the water balances of different operations into one "site-wide-water-balance"
 - ✓ How to tackle compatibility challenges
- ✓ Integration of water balance management to process control system of the mine

5. Monitoring and modelling solutions

5.1 Water quality and quantity monitoring

The water management program will include a water quality and quantity monitoring program. The process for setting up the monitoring program is a continuous process that progresses and develops (Figure 7). Monitoring starts before any excavations or alterations are made to the site and continues through to closure and after-care. The parameters for monitoring vary in the different phases of the mine life cycle and according to the water source and mine site.

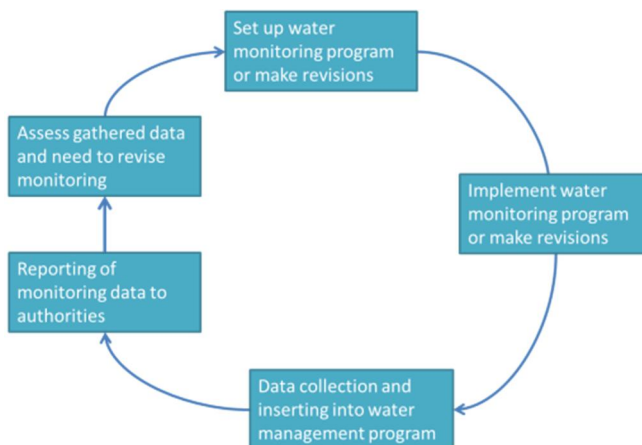


Figure 7. Continuous modifying of the water-monitoring process (modified from Department of Water Affairs and Forestry 2007).

A comprehensive water quality monitoring program recognizes all water sources and operating units in the total water balance equation, monitors all essential parameters, measures parameters reliably and at sufficient intervals, and links that data to the water management program. As the mine goes through the different phases in its life cycle, the water-monitoring program will change and even within a phase, as information and data are collected, knowledge increases and the need

to revise and update the monitoring program arises. The monitoring needs at the various life cycle phases are further described in Section 6.4.

Generally a mining company needs to know the performance of its enrichment plant and therefore attention is given to monitoring water entering the plant and the wastewater leaving the plant. On the mine site, water treatment facilities and other operating units are also monitored and their operations controlled well. The main topic of this chapter is the water monitoring in the rest of the mine site.

Pursuant to the permits, the mining company has to develop a water-monitoring program for the mine site and implement it in accordance with the reporting responsibilities so as to assess the environmental impacts of the mine activities. Many current mines may not have information on the conditions of the natural and fresh water sources of the mine site prior to commissioning. For example, groundwater quality before the commissioning of the mine has seldom been measured by many of the current mines. The changes in the conditions of the various water sources in and around the mine site should be measured in retrospect to their condition before the mine starts any of its operations. The current condition is primarily reporting of the yearly fluctuations in the conditions and the cumulative long-time trends and effects.

The operator needs to investigate what kind of harmful substances will be released into the air, water or soil from mining operations or beneficiation processes. Air emissions may also contaminate surface waters. The general bases for monitoring harmful substances are presented in Karvonen *et al.* (2012). Purified wastewaters should be investigated at least 12 times per year if the mining site includes a concentration plant and at least six times per year if there is only mining activities. Reliable risk analyses of harmful substance releases may change the quantity of sampling per year. Standardized or other reliable methods must be used when taking samples and analyzing harmful substances from surface waters. (Karvonen *et al.* 2012) Monitoring of mine discharge water should be done also for the natural water sources from wells and surface water (EALW 2010).

The content of the water-monitoring program for a specific mine site depends on the mine in question, plant design, surrounding grounds and waters, *etc.* The location of sampling points and monitoring sites should reflect all the possible environmental impacts of the mining processes. The parameters of the monitoring program are chosen case specifically, depending on the environmental load and effects of the mine. For example temperature, pH, DO, EC, Eh, COD, BOD, TP, TN, NO₃-N, N-NH₄, Cl⁻, SO₄²⁻, metals, suspended solids, turbidity, toxicity and/or bacteria analyses can be performed.

The water-monitoring program will contain detailed information on the parameters, sampling points, sample intervals, sample size and storage in accordance with the quality assurance of the mining company. It is a detailed and comprehensive program that fulfils the demand to monitor the effect of the mine operation on the environment. At best, it will also provide the mining company with important information on the operation of the mine and how to improve the water management and recycling program and therefore the economy of the site.

5.1.1 Monitoring of groundwaters and surface waters

A well-planned monitoring program provides comparable results and the development of water quality and quantity can be followed. An ongoing groundwater and surface water monitoring program should be implemented during mine dewatering to assess the impact of mining activities on water quality and the performance of chemical containment. This information will prompt changes to environmental management practices where necessary and will ensure that the contaminants that may impact natural waters and the environment will be detected and remedied effectively at an early phase.

5.1.1.1 Groundwater monitoring

The groundwater monitoring at a mine site is derived to show the impact of the mining on the environment. The groundwater monitoring consists of monitoring of the wells, household wells, and springs at the mine site and in its surroundings. Groundwater monitoring should be performed in all phases of the mine life cycle. The monitoring program design should be based either on regional or site-specific scales, mine type, phase, and design management. Groundwater monitoring during an early mining phase provides information of the baseline or background of groundwater conditions (quantity and chemical quality) before the mining construction and operations. Monitoring data also provides valuable input data for the development of the water balance model and groundwater flow model in early phases which can be used to estimate the available water storage for mine operations. Long term and continuous monitoring of groundwater level and flow to measure the temporal variation in different recharge periods provides the estimation of peak and low flows of surface leakage and runoff. The surface leakage points should also be investigated to ensure that the groundwater flow path remains within the system and to enable its control and management. This furthermore provides important information for mine infrastructure capacity and mine water management. From the mine construction and operations to the closure and after-care, the water quantity and quality monitoring program must exist to monitor the impact of mining operation activities and to determine the need to adjust treatment processes as required before discharge to the natural waters and the environment (Golder Associates 2011). The monitoring program should include the physico-chemical quality field measurements (e.g. T, pH, EC, Eh, DO, alkalinity) and groundwater level as well as the water sample(s) for geochemical analysis. The proper handling of the samples is crucial. In general, due to the reactive nature of mine waters, sample quality may change during the transport to the laboratory. For instance, the pH generally decreases and Eh increases after sampling, as a result oxidation and precipitation of iron and/or aluminium happens. Along with iron and aluminium, other elements may co-precipitate which decreases further the dissolved concentrations and increases the total concentrations in water. The chemical transformation during transportation is prevented through acid conservation immediately in the field as well as by transporting the water samples at

low temperatures. For the evaluation of dissolved concentrations, the suspended solids are removed through filtering. The filtering prevents also the dissolution of the particles into solution.

Since sample collection methodologies and techniques have been discussed in published literature (e.g. Van Heerden 1986, Ward *et al.* 1990, Mäkelä *et al.* 1992, Thomas & Grant 1992, Weaver 1992a–b, Pulles *et al.* 1995, 1996, Minerals Council of Australia 1997, Water Research Commission reports 1998–2001, Salminen *et al.* 1998, Suomen vesiyhdistys 2005, Heikkinen *et al.* 2008, Kauppila *et al.* 2011, Mine Closure wiki) they will not be addressed in detail in this report. In addition, it is always important to discuss with the analytical laboratory and have detailed advice on analyzing, preservation, and identification of the samples. Techniques and procedures vary from one laboratory to another. Special measuring equipment (weatherproof, robust, etc.) must be used in field conditions. Use, cleaning, and calibration must be done according to the instruction manual and recommendations of the manufacturer.

Spatial and temporal fluctuations of groundwater level depend on many factors, such as hydrogeological conditions of aquifer, groundwater extraction, and groundwater recharge that has a direct relation to the climate conditions. A groundwater monitoring program is needed for regular and long term monitoring of these fluctuations. The monitoring program should be implemented in parallel to local climate data measurements. Therefore, each mine should install at least one meteorological station to monitor the climate data, e.g., temperature, precipitation (rainfall and snowmelt), humidity, wind speed and direction, pan evaporation and radiation, and snow survey. Also monitoring of e.g. snow thickness, density and water-snow equivalent are recommended (Golder Associates 2011).

The Groundwater Studies Check List released in 2014 is a knowledge base that contains interactions of geology, chemistry and methodology. It can be used as an advisory list to ensure that all the needed knowledge of groundwater issues has been investigated using appropriate methods. In the checklist, the management of hydrogeological structure, groundwater flow pattern, groundwater - surface water interactions, transport of contaminants, as well as the issues concerning modelling and monitoring are perceived, and the optional methods for their determination are listed. The objective of the Groundwater Studies Check List is to help in communications between companies, consultants and authorities when groundwater issues are discussed (Tuominen *et al.* 2014, 2016, Kauppi *et al.* 2016), as shown in Table 3.

Table 3. The Groundwater Studies Check List is a metadata tool for groundwater risk management, including actual checklist, background paper and table for methods. This table is simplified version presenting main elements of the tool (Kauppi *et al.* 2016).

Task	Based on	Info on the subject	Quarter/person in charge	Progress measure	Schedule	More info
1 Data management in relation to hydrogeological structure						
1.1 Ground topography						
1.2 Soil stratigraphy						
1.3 Bedrock topography						
1.4 Fracture zones of bedrock						
1.5 Conceptual model of hydrogeological structure						
2 Data management in relation to groundwater flow						
2.1 Well survey						
2.2 Monitoring well installation						
2.3 Groundwater levels						
2.4 Hydraulic connections						
2.4.1 Thickness of saturated zone						
2.4.2 Interaction between groundwater and surface water						
2.5 Hydrogeological properties						
2.5.1 Hydraulic conductivity of soil						
2.5.2 Hydraulic conductivity of fractured zones of bedrock						
2.5.3 Storativity						
2.5.4 Porosity						
2.6 Conceptual model of groundwater flow						
3 Data management in relation to contaminant transport						
3.1 Concentrations						
3.2 Geochemistry of soil						
3.3 Groundwater quality						
3.4 Properties of contaminants						
3.5 Conceptual model of contaminant transport						
4 Modeling						
4.1 Hydrogeological structure model						
4.2 Water balance model						
4.3 Flow model						
4.4 Transport model						
5 Monitoring						
5.1 Investigations of the initial state						
5.2 Monitoring during operation						
Other, what?						

The Groundwater Studies Check List can be described as an array of best practices, common methods and novel techniques that can be used in groundwater investigations. It introduces alternative ways to achieve the required groundwater information. The checklist is applicable in any phase of a mine life cycle, and it is seen to improve transparency in groundwater protection and clarify the rules for documentation. The Groundwater Studies Check List provides an opportunity for the operator to assemble and present all completed groundwater investigations in a compact way, document all the methods used, persons in charge, and schedules and research needed in the future. (Tuominen *et al.* 2014, 2016, Kauppi *et al.* 2016) The checklist is available at: <http://www.syke.fi/groundwaterchecklist>.

The quality and quantity of groundwater at a certain point changes both seasonally and annually, which should be taken into an account when planning the water sampling. For example, in Finland the groundwater table is usually at its lowest level during July and August, thus leading to high concentrations of many

detrimental elements due to water exiguity. On the contrary, during the spring melt and autumn rainfalls the water amount is usually high and concentrations remain low.

Groundwater monitoring network should contain the following instruments:

- Groundwater observation wells and water level indicators
- Construction and operation of tubular wells or other drainage structure to perform the long term pumping test as needed
- Weirs for measuring the flow in springs and drainage network in the surrounding area
- Determining points and parameters for hydrochemical and biological monitoring and water quality measurements, and
- Weather station

Groundwater observation wells are the most important “windows” to groundwater. From a well like that depicted in Figure 8, it is possible to measure the quality and quantity of groundwater by online or field sampling. The materials and condition of the well make it appropriate for water monitoring. The best material for the monitoring well is plastic (HDPE), because it is less contaminant than metal wells. However, in some old observation wells and bedrock wells metal pipes are used. The water quality samples taken from these wells are not comparable with plastic well samples because of the possible contamination. Old observation wells should be restored and their good condition maintained during the years of monitoring. New wells should be installed if there are not enough appropriate wells in the area. Installation should be done and reported by experts according to best practices. Installed wells should reach the bedrock and sieves should be installed in the whole water permeable area. A large enough well size (about 50 mm in diameter) enables the use of versatile field equipment and powerful enough pumps. There should be a cap at the end of the pipe in order to prevent, for example, leaves and small animals from getting inside the well as well as vandalism. (Suomen Vesiyhdistys 2005)



Figure 8. a) Groundwater observation well. b) Taking a groundwater sample from private domestic well. (Photos: (a) Tiina Kaipainen, GTK and (b) GTK.)

5.1.1.2 Surface water monitoring

Surface water monitoring at a mine site is derived to show the impact of mining on the environment. The surface waters are monitored to show changes in their physico-chemical and biological conditions, the effect on the fish population and fishing as well as the changes in the aquatic sediment composition (Kauppila *et al.* 2011).

The surface water monitoring program must include the whole catchment area where the mine is located. The monitoring program normally includes flow measurement and water sampling. The physico-chemical analyses (such as T, pH, EC, Eh, DO, alkalinity) must be performed in the field together with the water sampling for the subsequent laboratory analyses. To characterize the quality of mine water and its impact on the natural environment, the hydro-chemical monitoring can be done in conjunction with flow rate and contamination loading assessment (Younger & Wolkersdorfer 2004):

$$\text{Contamination loading (g}\cdot\text{s}^{-1}\text{)} = \text{Concentration (g}\cdot\text{L}^{-1}\text{)} \cdot \text{Flow (L}\cdot\text{s}^{-1}\text{)} \quad (2)$$

The flow measurement with a long-term continuous hydrograph of the surface water should be collected together with meteorological data (*e.g.* precipitation, temperature) for at least over one year to cover the yearly seasonal cycles. The measurement frequency depends on the degree of fluctuation of water that corresponds to precipitation. Measurement frequency is high especially during peak flow periods after snowmelt and heavy rainfall events. Nowadays, long-term flow measurement gauging stations and networks are designed for automatic flood-warning systems.

Surface water samples can be collected directly from the water body or from, *e.g.* Thompson weir (V-Notch weir) (Figure 9). The samples can be taken from the upper part of the waterbody just below the surface or from different layers. (Mäkelä *et al.* 1992) The sample types can be divided up into following groups:

- **Grab samples** are taken from a specific point at a specific time. One sample is not representative but a series of grab samples may represent reality better.
- **Composite samples:** A mixture of several individual grab samples collected at regular and specific time periods, each sample taken in proportion to the amount of flow at the time. A composite sample provides an estimate of average water quality conditions and a better representative of characteristics of water over a longer period of time.
- **Stratified samples:** Samples from different layers of the waterbody from groundwater observation wells (packer methods) or from surface water (sample collectors).



Figure 9. Thompson weir (V-Notch weir) (photo: Tiina Kaipainen, GTK).

Flow measurement is carried out at the continuous flow monitoring station or “gauging” station, located at a point of interest in the surface water system. A long-term gauging station is normally designed with quantification of water resources or a flood warning system. (Younger & Wolkersdorfer 2004) However, the problem with measuring mine water flow is that often ochre precipitation on hydraulic structures and electronic sensors is found and because mine waters are very acidic, the corrosion of pipes or other metals can occur very rapidly. Therefore, special care must be given to regularly clean and maintain the mine water facilities. The following section presents applicable flow measurements based on PIRAMID Consortium (2003) and Younger & Wolkersdorfer (2004):

- The velocity-area method uses a current meter (impeller, heat-pulse or ultrasonic type) to determine the average velocities in a number of notional subsections of the width of an open channel. The total flow for the channel is obtained by summing the values of velocity and flow for each subsection.
- Hydraulic structures measurement is based on a predictable relationship between water level (stage) and flow rate (discharge). The scale of the suitable structure varies with the magnitude of the flow to be gauged and can range from large weirs in main river channels to large flumes, V-notch weirs or small H-flumes. Water levels behind hydraulic structures are typically measured using pressure transmitters or float and counterweight systems connected to optical shaft encoders. Electromagnetic and ultrasonic devices offer the potential for non-contact measurement of water levels, though the resolutions of the techniques are not always sufficient for accurate measurement of low and intermediate flows in open channels.

5.1.2 Monitoring of tailings ponds, seepage waters and dams

Current mine companies have water monitoring programs that comply with the permits set for the mine. Data collection, parameters for a specific site, and sample intervals are set out in the permit reporting specifications. In setting up the

monitoring program, the mine operations and its infrastructure have been the basis for deciding where the sample points are to be designated. For example, structural designs and materials need to be monitored if their failure may result in environmental accidents. The performance and reliability of the equipment will in the same way play a part in the contents of the monitoring program. The sampling points of importance to environmental impact are known to the mining company experts, and it is in the best interest of the mining industry that they foresee the possible weak/risk points on the mine site and monitor the related areas.

Hydrological conditions in Finland (surplus water) require monitoring the quantity of water in tailings ponds, reservoirs and basins to ensure that the capacity and sizing are sufficient. Information from the hydrological databases and stations will give the water balance model the expected seasonal and yearly increase in water level due to *e.g.* spring snow melting and autumn rainfall. These are to be accounted for by lowering the level in open water storage facilities. Local site conditions will also indicate whether flash floods are to be taken into account.

Monitoring seepage waters is an essential part of assessing the conditions prevailing on the mine sites. Signs of erosion and possible deterioration in constructions need to be noticed at an early stage before a major failure occurs. The mining company will know where to sample changes in pH and EC as well as turbidity to best monitor seepage and construction deterioration. 3D/4D ERT/IPT tomography is a non-destructive imaging technique used to image tailings, mining dams and hydropower dams as well as landfills and other industrial sites. The tomographic execution of electrical resistivity (ER) and induced polarization (IP) is a well-established method that is becoming more and more applied on embankment dams especially as a time-lapse, repeated monitoring technique.

The monitoring program related to the water management program is revised and updated as the need for changes is perceived. The implementation of the first version of the monitoring program will give light on the quality and quantity of the various water sources and their movements. As knowledge increases, the monitoring program will be revised in accordance with a specific mine site. The water system at the mine site is dynamic and will change with time thus requiring continual updating and revision of the water management and monitoring programs. Remediation of accidental spillages, *etc.* will also revise the program and it is cost-effective to take care of them immediately instead of leaving them for the after-care phase.

5.1.3 Monitoring sensors and analyses

The monitoring program that is set up for a mine site will give strict instructions on the requirements for all matters pertaining to monitoring the impact of the mining operations. In setting up the monitoring program, the mining company representatives have designated in detail all factors in the written water-monitoring program, for example, the parameters to be monitored, locations of the sampling sites, measurement intervals, sample preservation, measurement apparatus, calibration, data storage and so on.

The water-monitoring program will also include the requirements for the sensors and analyses to be used in water monitoring. All sensors acquired and analyses performed will be done according to the Quality Assurance Policy of the mining company. The results will therefore be reliable, but even so, it is good practice to refer analyses at predetermined intervals to an outside, accredited laboratory. This can be designated as a part of the water-monitoring program and the Quality Assurance Policy and will give the results added assurance and transparency.

The reliability and accuracy of the analyses and sensors used in the water-monitoring program have to be taken into account. Online water-monitoring sensors have the further burden of fouling and maintenance that are crucial in respect to their reliability. Also the condition of the measuring point (*i.e.* sludge removal from the channels, the condition of dam structures) affects the quality of the monitoring. The water quality and quantity data are used in the water management model and therefore their accuracy plays an important part in the accuracy of the model. This is especially important when sensitivity and risk analysis is performed for the water management model.

Monitoring of water quality and quantity can be divided into three categories: online, onsite/field, and laboratory analysis. Online monitoring is continuous measurement and data storage. Onsite or field measurements are performed immediately after the sample is taken for parameters that may change with time. The measurement is generally performed with field measurement apparatus and again in the laboratory along with the other chemical, biochemical, *etc.* analyses.

Depending on the measuring point, *i.e.* an open channel, closed pipe or groundwater, there is an array of flow meter types available with different properties from which to choose for each specific case. Flow measurement in an open channel needs a water level measurement for calibrations of the quantity of water.

Current online measurements mainly pertain to the quantity or flow of water. Until recently the quality parameters for continuous monitoring have been generally restricted to pH and electrical conductivity. There are two main reasons:

1. Most field sensors have a lifetime too short to make them an option for online measuring. Fouling, weather conditions and challenging measuring points would require attendance by mine personnel. The mines see the situation such that as long as maintenance and care of the sensors require frequent visits at the sensor sites the mine personnel can, with the same effort, take manual samples for laboratory analyses.
2. The investment and maintenance costs of analytical sensors have led to carrying out continuous water quality monitoring only at points where the information is of key importance.
3. To be able to measure online the same quality information data that is now being performed in laboratory analyses or even the major parameters would require many sensors, some of which are not even available presently. Therefore, manual samples would have to be taken to cover the whole array of

analyses needed. Consequently, most mine companies have opted to continue manual sampling.

Water quality online data collection is usually combined in a continuous flowing monitoring station where a pH and ionic conductivity are primarily monitored. Changes in these parameters are considered to give sufficient indication of changes in the water quality thus requiring further investigation.

Online sensors for measuring water quality used to be generally restricted to pH, EC and turbidity. The lifetime of such sensors is considerably less than flow meters and temperature sensors. Depending on the sampling point, the need to refresh the sensor at regular intervals to obtain reliable results will also increase the costs related to measuring. New techniques and equipment are also being developed as the necessity to obtain results online is increasing. However, these methods may need further development to reach the limiting values in the permits. State-of-the-art capillary electrophoresis (CE) is a quick method for measuring cations and anions in the laboratory. Online CE has been developed that can be situated in a shed to measure cations and anions from above-zero water flowing samples (Sprung *et al.* 2008). Electrochemical sensors (Räty 2013) and online sensors for altogether nearly 50 different water quality parameters (such as NO₂-N, NO₃-N, NH₄-N, turbidity, COD, DOC, TOC, DO, T and oil in water) and metals (such as nickel, cobalt, lead, iron, cadmium, zinc, mercury, copper, manganese and thallium) are under development or already available. According to the studies of online monitoring provider EHP-Tekniikka Ltd, the reliability of their online measurements (e.g. turbidity, suspended solids, and COD) can be better than with manual sampling and laboratory analyses. (Seppälä 2015) Also the investment and maintenance costs of online monitoring over the service life of 20 years are estimated to be around 30 % lower compared to manual sampling and laboratory analyses (Hiljanen 2015). EHP-Tekniikka has also developed a user interface that is able to handle several monitoring locations and their information (Figure 10) (Seppälä 2015).



Figure 10. On the left, EHP-Monitoring Station for water flow and quality monitoring in arctic field conditions can measure several parameters online, such as water flow/level, pH, EC, Eh, DO, NO₃-N, NH₄-N, T, COD, TOC, solids, and turbidity. On the right, a portable water level and quality monitoring device for wireless monitoring of groundwater and surface water level and quality in the field. Depending

on sensor, for example pH, EC, turbidity, T, Eh, NO₃-N, and NH₄-N can be measured. (EHP-Tekniikka Ltd 2015)

The second category of measurements is onsite or field analyses which are performed with portable equipment at the site of sampling. Field measurements are generally applied to parameters such as temperature, pH, EC, Eh, DO and turbidity and the results are correlated to the values obtained in the laboratory. Reliable sensors are available for field measurements of these parameters.

Monitoring

- ✓ Monitoring of groundwaters and surface waters aims to show the impact of the mining on the environment
- ✓ The water-monitoring program depends on the mine characteristics, surrounding grounds and waters *etc.*
 - ✓ Parameters, such as temperature, pH, EC, Eh, DO, alkalinity, anions, metals, N, P *etc.*
 - ✓ Groundwater monitoring: physico-chemical quality, groundwater level and flow conditions, in parallel with local climate measurements
 - ✓ Monitoring of surface waters: flow measurements, physico-chemical analysis
 - ✓ Monitoring of tailings, dams *etc.*
 - ✓ Weather data: own weather station if possible
- ✓ Monitoring tools: online, on-site/field and laboratory
 - ✓ Online: flow, water level, pH, T, EC, turbidity, NO₃-N, NH₄-N *etc.*
 - ✓ Field methods: pH, T, EC, Eh, turbidity, DO

The third category of measurements is those performed in the laboratory. The list of parameters to be analyzed will depend on the mine and be site-specific: e.g. pH, DO, EC, TDS, suspended solids, COD, BOD, TP, phosphate phosphorus, soluble phosphorus, TN, NO₃-N, NH₄-N, toxicity, bacteria in addition to the metals and ions specific to that mine operation. The analysis techniques and methods available for these analyses are well known.

The environmental permit of a mine usually includes chemical analyses of water to monitor environmental impacts. However, due to the reactive nature of ions in solution, the chemical composition alone does not reveal all the hydrological and chemical processes controlling the contaminant fluxes at the mine site. Coupling major solute concentrations with tracer tests allows a more detailed evaluation of mine water-environment interactions (Younger *et al.* 2002). Further, both tracer test and geochemical analytical results can be applied in hydrogeochemical modelling for the prediction of chemical transformation and long-term impacts of mining at a study site and its surroundings. Tracer test have been used for several years to study groundwater flow velocities, and paths, hydrogeological parameters of the catchment area as well as surface water-groundwater interaction. In fact the first tracer tests were already used in Roman times (Wolkersdorfer 2008). In mine sites tracer tests provide additional insights into water mixing, contaminant source, transport pathways and attenuation at and near mine sites. Since many mines face problems assessing the source and pathway of groundwater contamination

especially in underground mines, the tracer tests are a rather easy and inexpensive method to investigate the hydraulic behaviour of the mine water in the mine site and its surroundings. Moreover, locating the source of contamination usually decreases also the costs of water treatment as the contamination may be possible to treat already in source instead of discharge site. In addition, a tracer test can be used when evaluating the feasibility of waste disposal sites. (E.g. Younger *et al.* 2002, Wolkersdorfer 2005, 2008)

There are two types of tracers: natural and artificial tracers. Natural tracers such as isotopes, organisms or even physical qualities of the water occur naturally or unintentionally in waters. In contrast, artificial tracers such as dyes, salts and solid tracers are injected on purpose into the water. (Wolkersdorfer 2008) There are numerous natural tracers found in water systems that can be used over large areas and long timescales when studying hydrological connections and pathways. For instance, stable and radiogenic isotopes exist naturally in waters and the differences in isotopic concentrations reflect either the natural hydrological phenomena (e.g. O and H) or the characteristics of the local bedrock and soil (e.g. Sr and U). In addition, the chemicals used in ore processing or water treatment leave chemical tracers that can be used as a pinpointing tool for mine-related emissions. Chemical tracers are categorized also as natural tracers since they are not injected on purpose into the water, but entered the water either due to accident or slow contamination. (E.g. Lippmann *et al.* 2003, Wolkersdorfer 2008, Younger *et al.* 2002, Larkins *et al.* 2016) Since artificial tracers are often reactive in mine waters (e.g. Na-fluorescein) or expensive (e.g. bromides) or their use might be restricted or require permission (e.g. radioactive tracers), natural tracers are nowadays more commonly used. In contrast to artificial tracer studies, due to their natural occurrence in waters, natural tracers are rather inexpensive and easy to conduct. Further, although using natural tracers usually requires more sampling sites due to the lack of controlled injection, the monitoring required by environmental permits commonly includes geochemical analyses of water that should be taken even without tracer test study.

A comprehensive hydrogeological study precedes all tracer tests. This is needed not only to reveal water flow paths but also to choose injection and sampling sites. In addition, at least the following characteristics of the watershed area should be known before conducting a tracer test study (modified from Wolkersdorfer 2008):

- Surface water and groundwater areas, flow directions and velocities
- Lithology and hydrogeochemical parameters, and
- Water use (e.g. private and public wells, dewatering, raw water supply).

Although tracer tests have been proved to be an effective tool to study mine water interactions and contaminant transport, no tracer test is simple to conduct. Hence, all tracer tests should be conducted by experienced consultants or research groups. A more detailed study on the utilization of geochemical and isotopic meth-

ods and tracer tests in mine water studies are presented, *e.g.* in Younger *et al.* 2002, Suomen Vesiyhdistys 2005, Wolkersdorfer 2008, Larkins *et al.* 2016.

5.1.4 Water quality and quantity data for water management

In setting up the water management program, the model requires reliable data on the quality and quantity of the various waters located on the site and included in the program, *e.g.* groundwaters, surface waters, catchment areas, seepage waters, and tailings ponds. The Quality Assurance Policy of the mining company will ensure the reliability of the data and is of high importance. When the water-monitoring program is set up, it is vitally important that the results reported for each parameter are of the highest quality possible, thus requiring that, for example, the following points are designated to obtain that goal:

- Analysis equipment, calibration, maintenance
- Analysis method, verification
- Sensor quality, calibration, maintenance
- Sampling including sample size, intervals, right timing
- Number of replicate samples

The list is long, but this is routine for a high quality, accredited laboratory. In Finland, control analyses are performed at an outside accredited laboratory to further ensure the reliability of the results. This requirement will be set in the mining company's environmental permit. If the mining company has its own laboratory it will perform in-house analyses and regularly check their own results against control samples performed at an outside laboratory thus increasing reliability and transparency.

The ideal situation would be to have continuous online data gathering for the water management program, but generally mostly only physical parameters such as temperature, pressure, and water level, amount and flow, and quality parameters pH, ionic conductivity and turbidity are currently gathered by the program online through monitoring sensors and equipment. Although there are more online sensors available for measuring water quality parameters, and some mines have been active in applying and testing new technologies, the chemical analyses are mostly still performed offline. The water management program must therefore allocate inputs for the addition of onsite/field measurements and chemical analysis data. A user-friendly interface of the water management software shows the water quality and quantity data from both online and input measurements thereby allowing reacting to perturbations and trend changes.

The general aim and requirements for water quality monitoring will be universal the same even though the monitored parameters, and sampling details, *etc.* will be site-specific. The acceptable water quality values for each monitored measuring site will be set so that they are in compliance with the water quality criteria. The mining company will define trigger levels to indicate whether the water quality is degrading, *e.g.* 25%, 50%, and 75% of the level that complies with the water quality criteria.

The follow up of water-monitoring data will show the trends in the levels of the water quality criteria parameters and alert when the trigger levels set by the mining company or permits are exceeded. The quality of the mine waters at the monitored sites that can be seen as posing a potential hazard to surface waters and groundwaters are monitored and compared to the baseline water quality data gathered before any alterations were performed to the mining site. Baseline and impact assessment studies on the aquatic environment are essential to qualify for legislative requirements and to entitle mining operations. (Janowicz 2011)

5.2 Modelling

The awareness of actual water quantities and water balances in mine areas gives the possibility to forecast the behaviour of water masses in the future. Water and mass balance models are important decision support tools for mine operators and regulators (Janowicz 2011). They offer a valuable approach to accounting for and managing the volumes of water entering, leaving and circulating throughout the mine site (IM Mining 2013). Basically, such models help the operators with site water management and the regulators in assessing whether environmental effects on water quality will potentially occur as a result of mining operations (Janowicz 2011). However, although a water balance model is a good tool to enhance water management, it should be understood that it is just one tool amongst others (such as data sampling, data management, online measurements) that can be utilized to address issues and to develop policies to steer mine waters, and to achieve a goal that is set for water management (Mueller 2015).

For example, water and mass balance models can be used to justify water management measures, to develop and communicate strategies, to plan and design infrastructure within the site, and to evaluate risk (both planning and operational) and uncertainty factors related to current and prospective mine water management actions (Janowicz 2011, Mueller 2015). Modelling also allows the comparison of different mine plan alternatives and estimation of potential environmental impacts and cumulative effects (Janowicz 2011). In fact, one of the key issues in water balance modelling is just the possibility to develop different strategies based on the simulations, and to test these strategies. The real power of modelling comes from the ability of models to simulate and evaluate identified risks, understanding the behaviour of the system under dynamic conditions or the effects mining has in the downstream. (Mueller 2015)

5.2.1 Model development

Development of a good water balance model begins at an early phase in the mine life cycle, *i.e.* during the initial feasibility and planning phases. According to Haanpää (2013), the model development should include the following phases:

- Definition of model objectives
- Development of conceptual model

- Selection of modelling platform
- Determination of key limiting factors (e.g. maximum effluent water amount)
- Determination of general limitations
- Collection of input data
- Quality assurance
- Calibration and validation
- Sensitivity analysis
- Comparison of results to limiting aspects
- Recalculations
- Reviews. (Haanpää 2013)

Mueller (2013) also illustrates the model development process, as shown in Figure 11. Both of these approaches contain basically the same aspects although the orderings of different steps, e.g. the development of a conceptual model, are a bit divergent at some points.

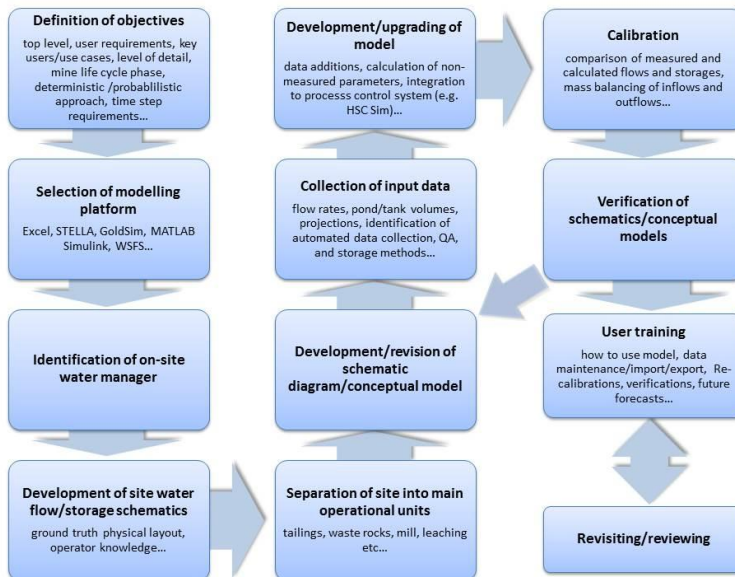


Figure 11. Water balance model development (modified from Mueller 2013. NB the insertions “integration to process control system [e.g. HSC Sim]”, and the software “MATLAB Simulink, WSFS” were not mentioned in the original source).

Conceptual model development is a key process for achieving an effective water balance model (Maest *et al.* 2005, Mueller 2013) and needs to be done before the actual modelling. A conceptual model offers an understanding of the system to be modelled and the critical factors that have effects on its behaviour (GoldSim Technology Group 2014a). In mine water management, a conceptual model can be described as a qualitative description of the chemistry and hydrology of a specific

mine site and the effects they cause on natural and mined materials (Maest *et al.* 2005). The development of a conceptual model is a gradual process consisting of the following seven phases (Mueller 2013):

- Conceptualization on a high level based on the arrangement of different mine facilities and flow connections between them
- Contemplation of the prime purposes of the model
- Development of a water balance sub-model for different facilities
- Recognition of repositories of measured data
- Framing of approaches for non-measured data
- Development and testing of model
- Iteration of the revision needs of conceptualization. (Mueller 2013)

The accuracy of the model conceptualization should be so good that it allows the user to simulate different scenarios where water management is modified causing a change to either the flow volumes or the water quality. These modifications can include whatever phenomena in the mine site, *e.g.* waste rock cover systems, discharge water treatment, discharging without treatment, and different pump-back options, *etc.* (Water Engineering Australia 2011)

The modelling objectives should be clearly defined at the starting point of the modelling process. After the definition of the objectives, one of the following tasks is to choose a suitable platform for the modelling. Modelling is commonly performed either using spreadsheets (deterministic modelling) or general purpose simulators (dynamic approach). The model should involve the whole mining area and all of its functions over the whole life cycle of the mine. Each operational unit of the mine is modelled separately. (Janowicz 2011) This enables the generation of separate balances for smaller units as well as an overall integrated balance (Department of Water Affairs and Forestry 2006b).

It is advisable to use common and equal formats and methods over the whole mine site. The water balance system should also be flexible to changes. To achieve an adequate resolution of the balance, the water flows for each circuit type should be considered down to an accuracy level between 1% and 5% of the total. Measurement errors and inaccuracies should also be recognized and perceived. (Department of Water Affairs and Forestry 2006b)

In large or long-lasting mining projects, modelling is usually performed only for selected periods because modelling the entire life cycle would easily become too arduous. Modelling selected periods can be done in two ways, either modelling water quality and quantity a) for each selected period over one year, using different climate scenarios, and/or b) over a longer time period (for example 50 years), using the prevailing circumstances of the system at issue for the selected period for the whole simulation time. (Janowicz 2011)

The following input needs to be collected for the water balance modelling (Janowicz 2011):

- Process and dewatering data (data from mine plan, production characteristics, other operational processes/constraints, amount of dewatering waters)
- Physical data, such as topography, land uses, associated runoff coefficients, storage, flow and/or pumping capacity of different infrastructure components
- Climate data, such as precipitation, temperature, snow situation, evaporation
- Hydrological and hydrogeological data, such as local runoff, flow time series, flow regime, groundwater conditions such as seasonal elevation of groundwater table, flow direction and rate, recharge rate, possible artesian conditions
- Water quality data, such as time series of concentrations/loadings (all quality constituents, all sources). (Janowicz 2011)

The model can also contain, for example, stochastic rainfall data and uncertainties which can be used to predict extreme weather conditions (Water Engineering Australia 2011).

The water balance model outputs include water flows and volumes/levels, together with the water qualities at the selected points in the mining area (consisting of the receiving environment and mine effluent release points). Sensitivity and uncertainty analyses are performed to determine what kind of impacts may occur in water quality and quantity model results if the values of model inputs are changing. In addition, an understanding of the interactions between the inputs can be achieved. (Janowicz 2011) Although water balance estimations are often said to be precise, there are always uncertainties caused by inadequate data capture networks, errors in measurements, and the complex spatial and temporal heterogeneity that is a typical feature for hydrological processes. An uncertainty analysis can act as quality control for the data gathered and is a significant part of the water balance estimation. Problems may also arise, for example, if the spatial and temporal boundaries are not specified, the input data quality is not sufficient, intuition rather than good quality data is used, water flows are double-counted, extrapolation of field-scale information to a larger scale is inappropriate (as many hydrological relationships are dependent in a scale), the storage term(s) is omitted, or political or some other types of pressures are resulting in manipulated unreliable estimates. (Moriarty *et al.* 2007) An appraisal of climate change impacts on the results may also be included in the sensitivity and uncertainty analyses (Janowicz 2011).

5.2.2 Modelling software

A variety of software products for modelling exist. In Sections 5.2.2.1 and 5.2.2.2 an overview of some of the most well-known deterministic and dynamic modelling approaches currently in use is presented. The comparison of the various models is mostly based on the information provided by the software companies. Dynamic models can be coupled, for example, to hydrological, geochemical, economic, reactive transport and chemical equilibrium models, each module having a specific

case for which it is best suited. These model types are described more specifically in Sections 5.2.2.3 and 5.2.2.4.

5.2.2.1 Spreadsheet-based models

Spreadsheet-based programs are widely known and therefore also commonly used in modelling. Their use is mostly focused on deterministic modelling, but it is also possible to construct a dynamic model using a spreadsheet and thus be able to simulate the behaviour of a system over time. If the issues related to time and non-linear relationships can be solved, building a stock-and-flow model in a spreadsheet is conceivable. (Ford 2010)

A spreadsheet can act as a dynamic modelling tool if a specialized add-in program is used. Several supplementary software products, for example the @RISK and Crystal Ball programs, are capable of incorporating probability distributions into the spreadsheet, and risks and uncertainties can be analyzed (McPhail 2005). These probabilistic software programs are able to simulate any type of spreadsheet originated system. As most people are familiar with spreadsheets, these programs may seem more easily accessible to the user than other simulation software. (GoldSim Technology Group 2014a)

Spreadsheet-based deterministic modelling can be rapidly implemented and at best, spreadsheets are able to provide very exact information on the case at hand. With the help of spreadsheet-based models, a good general idea of the site water balance can be achieved. (Haanpää 2013) It is also possible to see all the numbers used behind the modelling (Ford 2010). According to the software competitor GoldSim, spreadsheets may be a very useful tool when the aim is to make easy projections or account tasks. Spreadsheets are also more suitable than GoldSim in assembling large data amounts quickly and making calculations in a single view. (GoldSim Technology Group 2014a) However, spreadsheets have certain deficiencies, such as:

- Spreadsheet models are not transparent or dimensionally aware
- Complex models may be difficult to interpret and explain to others
- Model structure cannot be displayed graphically
- Add-ins are needed to assess uncertainties
- Models are prone to errors
- Spreadsheets are not well-suited to simulate highly complex dynamics (GoldSim Technology Group 2014a), and
- Spreadsheets are not very adaptable to different scenario inspections (Haanpää 2013).

Microsoft Excel is probably one of the best known spreadsheet environments currently existing. In co-operation with advised engineering judgment, simple Excel-based water and mass balance models may be suitable tools in achieving

basic level cognisance of water movement within the mine development area together with predicting qualities of effluent waters over a certain range of operating and climatic conditions. Models may provide useful early-phase information when assessing the capacity required in implementing applicable mine water management infrastructure. The Excel spreadsheet model can contain, for example, the following input and output sheets (Janowicz 2011):

- Introduction of the template (input)
- Description of water balance model (input)
- Climate parameters (input)
- Operating data and flows involved in ore processing (both input and output)
- Flows related to runoff from precipitation (both input and output)
- Evaporation losses, seepage, and other flows (output)
- Water balance module, modelled flows per sub-watershed (output)
- Mass balance, qualities of effluent and receiving water (both input and output). (Janowicz 2011)

Naturally, model adjustments are essential during the process development. However, the use of a spreadsheet-based model may eventually limit the modelling flexibility of a mine development phase. At some point, as the model develops, it becomes too demanding to operate, maintain and update due to the time-consuming simulation periods and complexity of model. Although more complex models are needed in later phases of the mining project, Excel-based modelling can support dynamic modelling and provide input into these models. (Ford 2010, Janowicz 2011) For example, spreadsheets may be used to store, display, and check dynamic model inputs, or display and analyze dynamic modelling results (Ford 2010).

5.2.2.2 Water balance simulators

Although spreadsheets can be used for simulating behaviour over time, specialized simulators offer a clear and easier approach to dynamic modelling and thus their use can be justified (Ford 2010). Voinov (2008) classifies dynamic modelling software as modelling systems and extendable modelling systems. Modelling systems, such as STELLA and Vensim, are said to be wholly pre-packaged, and no additions to the provided methods can be made by the user, whereas specific codes can be added to extendable modelling systems, such as MATLAB Simulink and GoldSim, if the existing method is not suitable for the specific modelling purpose. According to Ford (2010), STELLA, Vensim, and Powersim are amongst the most common programs for environmental modelling to implement system dynamics. These software programs are visually very alike. In related software such as GoldSim, MATLAB Simulink, and Simile, the icon-based user interface can also be

used for numerical modelling. (Ford 2010) STELLA, Vensim, MATLAB Simulink, and GoldSim are described more closely in the following sections as the references of their use in the mine water management were found in the literature. In addition, the Watershed Simulation and Forecasting System (WSFS) is presented. A water balance flow diagram for conceptualization of the model components needs to be developed before using these simulators as it helps to recognize the essential building blocks required to illustrate the water management infrastructure and operations on the mine site (Janowicz 2011).

STELLA

STELLA (Structural Thinking Experiential Learning Laboratory with Animation) software is developed by isee systems (Formerly High Performance Systems). STELLA is one of the first well-known dynamic system modelling software programs for constructing models capable of simulating different kinds of systems in a realistic way. STELLA has a user-friendly, easy, and intuitive icon-based graphic interface (Costanza & Voinov 2001, Janowicz 2011, Rice *et al. undated*) to simplify the modelling of different dynamic processes (Costanza & Voinov 2001, Janowicz 2011).

STELLA uses four different basic blocks for building a model: stocks, flows, connectors, and converters. The operation of STELLA is based on manipulating these blocks. Mathematically, STELLA solves differential (difference) equations that are generated for each of the stocks by placing icons in the modelling area. Stocks are tangible, countable, physical accumulations representing a reservoir of material (e.g. water) that is connected to the point of interest. Stocks are connected either by flows of material (material either flows between defined stocks or into/out of other sources or sinks) or informational relationships. Only flows can change the magnitude of stocks. Flows are affected by auxiliary variables (constants, mathematical or graphical functions, and data sets), stocks, and other flows. The use of a converter modifies an activity and can store constant values or equations. During every time interval of an ongoing simulation, equations generate an output value. Converters are able to transform information for use by other model variables. Connectors transmit data inputs or outputs to regulate flows. Connectors cannot have numerical values, and unlike flows, they cannot go into a stock. (Costanza & Voinov 2001, Shiflet & Shiflet 2006, Rice *et al. undated*)

Basically, three different phases are needed for constructing the simplest form of STELLA model. First, stocks need to be defined to construct a quantitative model. In this phase, links to different variables affecting the size of these stocks are generated, which in many cases are direct inputs/outputs that are modelled using flows. Converters can adjust the extent of flows by using links. Also the size of the stocks in a density-dependent manner can affect the extent of these flows. The second phase in the modelling construction, parameterizing the model, allows quantifying both linear and non-linear relationships among the elements. The final phase consists of exploring the model's dynamics. After running the model, model

outputs are generated and the outcomes can be studied either quantitatively or qualitatively. Sensitivity analysis may also be performed. (Rice *et al. undated*)

According to Janowicz (2011), STELLA has many benefits compared to simple deterministic spreadsheet models. These advantages include:

- Its dynamic nature allows the simulation of system over time
- The software generates model equations automatically
- It enables sensitivity analyses
- The model can be broken down into smaller sectors and run independently if only certain sectors, modules or model time frames are of interest
- It clearly communicates the inputs/outputs of the system and illustrates the outcomes
- The model enables data import/export to Microsoft Excel. (Janowicz 2011)

Vensim

Vensim systems dynamics software is developed by Ventana Systems Inc. Vensim is general purpose simulation software for modelling dynamic complex systems. It can be used to develop, analyze, and package dynamic systems having feedbacks (Ventana Systems 2014). The ideology of Vensim is very similar to STELLA as it uses the same stocks-and-flows in describing the systems (Voinov 2008, Ford 2010). Vensim is also visually similar to STELLA (Ford 2010). The important functionalities of Vensim include automatic model calibration, model optimization (using an efficient Powell hill climbing algorithm), reality checks (statements about reality can be checked against behaviour generated in a simulation model), sensitivity testing (using Monte Carlo analysis), subscribing (language used to construct highly advanced arrayed models), causal tracing (tree diagrams are used to find the variables that cause a selected variable to change, and the use of this certain variable or its behaviour), and custom applications (for example, Vensim DLL program enables co-operation with other applications like Excel). (Voinov 2008, Ventana Systems 2014)

MATLAB Simulink

MATLAB, developed by MathWorks is a commonly used technical computing environment intended for numerical computing, programming, and visualization. MATLAB can be used for data analyses, algorithm development, and creating models and applications. Simulink is a general purpose simulator that can be used for modelling, simulating and analyzing multi-domain dynamic systems. Both continuous and discrete time systems can be modelled with Simulink. Simulink is integrated into MATLAB which allows importing MATLAB algorithms into models, and on the other hand also results from simulations can be exported back to MATLAB and analyzed further. Simulink uses a graphical user interface and a

customizable set of predefined block libraries for building and managing block diagrams. The nature of Simulink model is hierarchical (MathWorks 2014). The hierarchical model structure enables model segmentation and the use of top-down approaches, thus allowing the management of complex designs (Janowicz 2011).

The Simulink modelling environment supports fast development and analysis of time- and event-driven models which makes it a useful tool when modelling mining related processes. Simulink incorporates a breadth of mining-related applications, its flexibility allows the adjustment of simulations alongside the changing mining operation, and common language enables easy communication between management and engineers. These are among the main characteristics and reasons why Simulink is used in the mining industry. (MathWorks 2014)

The main capabilities of Simulink include building and simulating models, analyzing simulation results, and easy project and data management. The model-building phase begins with selecting the appropriate blocks for modelling. Simulink includes continuous and discrete dynamic blocks, algorithmic blocks, and structural blocks which can be used for building customized functions. The model is built by dragging the appropriate blocks into the editor and connecting them with signal lines representing mathematical relationships between the components. A model hierarchy can be added at this point. In the model-building phase, navigating through the model hierarchy and managing signals and parameters are possible. Time-varying data is illustrated using signals, while the parameters define the system behaviour and dynamics. In the simulation phase, the dynamic behaviour of the system is modelled. The results can be viewed as the simulation runs. Fixed-step and variable-step ODE solvers, a graphical debugger, and a model profiler can be used to guarantee simulation speed and accuracy. Simulations can be performed either in normal or accelerated modes by using Simulink Editor or MATLAB. After the simulation phase, the results can be analyzed by using Simulink or MATLAB. To be able to better understand the simulation behaviour, debugging tools are incorporated into Simulink. (MathWorks 2014)

Ford (2010) sees that dynamic modelling is more productive and easier with STELLA or Vensim than with Simulink. In his opinion, however, the key advantage of Simulink is its position within MATLAB, which is versatile, easy to use, and offers a substantial collection of functions. (Ford 2010)

GoldSim

GoldSim, developed by the GoldSim Technology Group, is icon-based general purpose simulation software for dynamic modelling of complex systems (GoldSim Technology Group 2014a). GoldSim offers a visual simulation environment with a large number of different modelling capabilities, e.g. both logical and discrete events can be modelled (Mueller 2013). GoldSim provides the features and flexibility to simulate almost any process related to business, engineering and environmental applications (GoldSim Technology Group 2014a).

GoldSim is well-known also to the mining industry and has a large group of users (Mueller 2013). The model characteristics are suitable for mining-related mod-

elling (GoldSim Technology Group 2014a). It can be used to address a broad range of issues related to mine water management, for example, to sustain different water management scenarios, carry out uncertainty and sensitivity analyses, simulate mass balance water qualities, and design the site's infrastructure (Janowicz 2011). GoldSim is commonly used in mine water balance studies in Europe, North and South America, Africa and Australia. In addition, mining companies also use GoldSim in assessing transportation of contaminants, environmental impacts, different closure options, and performance of process operations. Management and logistics of mine materials also benefit from GoldSim simulations. (GoldSim Technology Group 2014a) (Figure 12)

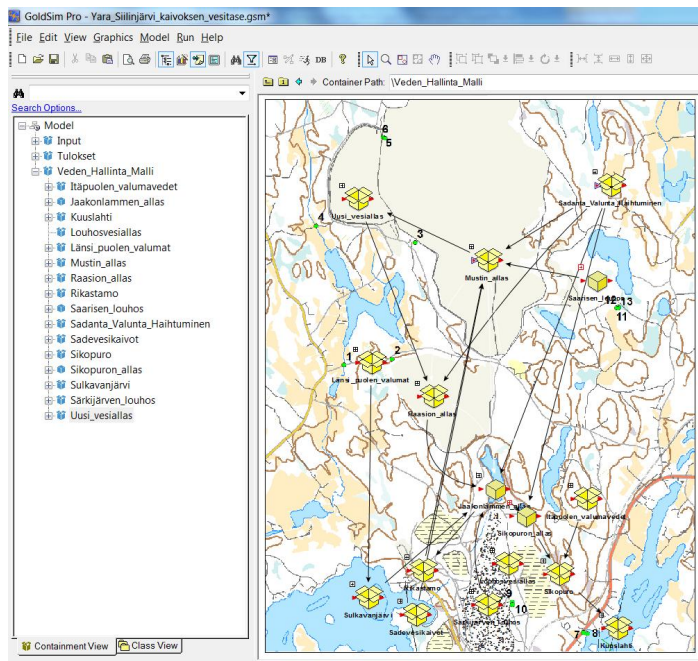


Figure 12. GoldSim has been used to model water balances also on Finnish mine sites (picture: Juhani Korkealaakso/VTT).

Dynamic models differ in cost and complexity. At least in 2005, GoldSim was the most extensive modelling environment available but at the same time also the most expensive modelling code. (Maest *et al.* 2005) The flexibility of a general-purpose simulator and highly graphical probabilistic simulation environment are combined in GoldSim. The graphical, object-orientated and hierarchical structure of GoldSim, and the use of modules and subsystems that are linked together along with other specialized programming options enable the development of highly complex models that are yet easily interpretative (GoldSim Technology Group 2014a). Also more intuitive representation of the water management units

and their operations can be developed (Janowicz 2011). Graphically, GoldSim models mix visual and mathematical symbols (Ford 2010). GoldSim entails certain pre-coded objects that can be used in water balance applications (Nalecki & Gowan 2008). Furthermore, the software contains object types which can be coded and customized by the user depending on the specific modelling needs (Nalecki & Gowan 2008, GoldSim Technology Group 2014a). GoldSim is a strong choice for use in mine-specific and site-wide modelling as it allows the integration of multiple data streams and the integration of water quality and water balance information (GoldSim Technology Group 2014a). For example, the codes used in hydrogeochemical modelling, surface and groundwater flow modelling as well as in geotechnical simulations (PHREEQC, TOUGHREACT, *etc.*) or at least their dynamic output can be linked into GoldSim to build an integrated, site-wide and mine-specific simulation tool. GoldSim is also the most important Monte Carlo simulation software solution for analyzing uncertainties, and it is able to express model uncertainties explicitly (GoldSim Technology Group 2014a).

GoldSim has many advantages over spreadsheets for building complex, quantitative models, as certain limitations arise when spreadsheets are used for modelling dynamic processes and many quantitative modelling tasks (Janowicz 2011, GoldSim Technology Group 2014a). GoldSim also differs from system dynamic software that is based on stocks and flows and demonstrates the feedback structures of the system (such as STELLA, Vensim, and Powersim). Although similarities exist between GoldSim and these products, GoldSim is able to provide more realistic simulation data of complex systems and their future performance. (GoldSim Technology Group 2014a) GoldSim differs from other modelling approaches presented in previous sections due to the following characteristics:

- The modelling capabilities of GoldSim are very versatile. A wider selection of model objects exist in GoldSim compared to other dynamic software solutions, which makes GoldSim-based models logical and their structure more transparent. The transparency and robustness of GoldSim models are also better than with spreadsheets. GoldSim takes into account the concept of time and is thus better suited to simulate complex dynamic systems that evolve over time than spreadsheets. (GoldSim Technology Group 2014a)
- The GoldSim model is very flexible. By using the same base model, it is possible, for example, to perform both deterministic and probabilistic simulations, alternate simulation periods, model varying time-dependent conditions (such as process water sources and sump operations) over the mine life cycle, and incorporate water quantities and qualities. (Janowicz 2011)
- Almost all real-world systems are influenced by uncertainties as well as stochastic processes and events, and predictive modelling must be able to handle these features. Spreadsheets, for example, are not able to naturally handle uncertainties or random events. GoldSim has the ability to explicitly represent such aspects as the software was especially developed to understand uncertainty factors and stochastic mechanisms (GoldSim Technology Group

2014a). Thus, GoldSim is able to clearly express uncertainty issues related to water management systems (Janowicz 2011).

- The occurrence and consequences of discrete events in continuous systems can be successfully modelled using GoldSim. (GoldSim Technology Group 2014a)
- Other modelling alternatives may not be dimensionally aware. That is, they do not understand different types of units or dimensions, which also makes them sensitive to errors. GoldSim understands all types of units and performs dimensional consistency checks and unit conversions automatically. (GoldSim Technology Group 2014a)
- GoldSim uses specialized extension modules (such as the contaminant transport module, reliability module and financial module) which are able to address systems that cannot be sufficiently modelled using the stocks and flows (GoldSim Technology Group 2014a).
- GoldSim can interact with a large group of external file formats, such as Microsoft Excel (Janowicz 2011). GoldSim works seamlessly with spreadsheet models and information can be dynamically passed to and from spreadsheets during the modelling process (GoldSim Technology Group 2014a).
- GoldSim can ease the interpretation of complex spreadsheet models (GoldSim Technology Group 2014a).
- The accessibility and ease of use are better in GoldSim as there is a free version available (GoldSim Player) with limited functionalities, allowing anyone to view and run models created by authorized users (GoldSim Technology Group 2014a).

The GoldSim model can be delivered as a self-contained GoldSim Player file which is operable by the freely distributable GoldSim Player executable. The intention of the Player file is to be intuitive for the end-user, report needed results and to allow for any anticipated changes in numerical input terms. A limited number of options can be provided that reflect different water management strategies, but not all real-world possibilities can be incorporated in these options without the quantitative definition of the management options. Models created using GoldSim Authoring tools allow the creation of custom interfaces or dashboards into these Player files. Buttons, input fields, sliders and result displays can be included in these interfaces. Embed text, tool-tips and graphics can also be included in the dashboard to provide instructions on using the model. (GoldSim Technology Group 2014b)

The contaminant transport module of GoldSim enables simulation of different chemical processes such as solubilities and partitioning. These processes are simple, easily configurable and flexible, but cannot be used to illustrate complete reaction paths because additional chemical relationships may be required to simulate complex hydrochemical systems. Complex chemical processes of chemical

equilibration and aqueous speciation can be modelled by integrating the dynamic link library (DLL) element of GoldSim with PHREEQC. (Eary 2007) (Figure 13)

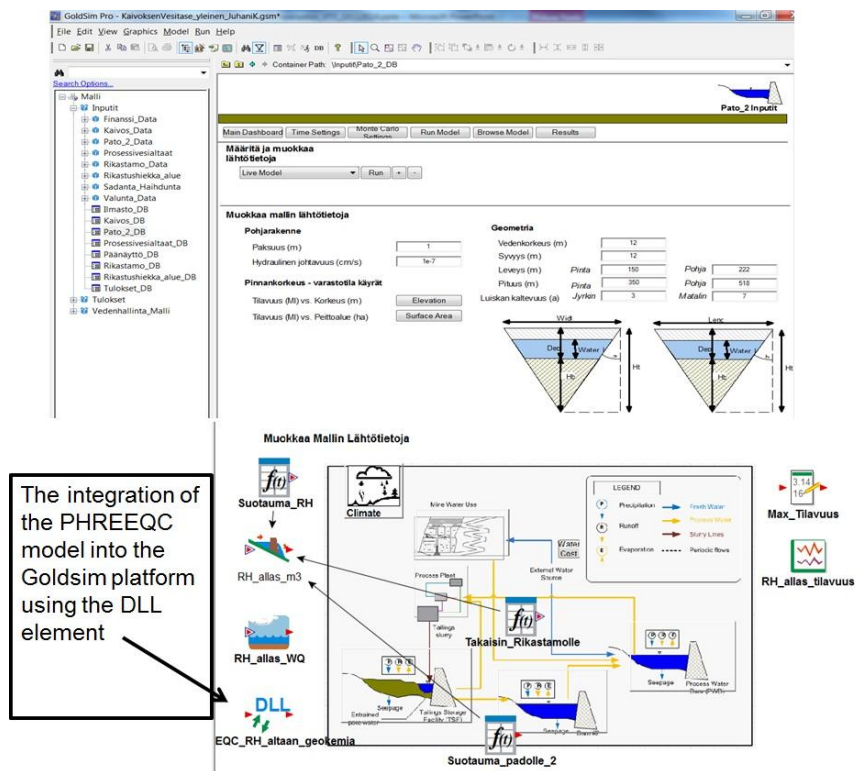


Figure 13. The integration of PHREEQC into GoldSim (picture: Juhani Korkealaakso/VTI).

Usher *et al.* (2010) present an approach that can be used to connect empirical and theoretical geochemistry. In their work they link site-specific mine waste characterization results and mine water balances together to predict the quality of mine water derived from waste sources. Geochemical responses from on-site monitoring, kinetic field tests and laboratory results have been linked to PHREEQC to recognize the main geochemical processes occurring in the site. Based on the data from static geochemical tests to populate the models, defined geochemical generation rates, geochemical properties of the site and water balance of the mine site, the role of GoldSim is to realize the conceptual understanding of different aspects and build a framework to provide water quality projections on a mine scale. (Usher *et al.* 2010)

Watershed Simulation and Forecasting System (WSFS)

The sophisticated systems with sensor-based processors are already widely used in hydro-meteorological data collection and the corresponding forecasting system, the Watershed Simulation and Forecasting System (WSFS) based on the data collection, operates throughout the territory of Finland at the river basin level (Vehviläinen *et al.* 2005, Veijalainen *et al.* 2010, Bergström *et al.* 2012). The program is developed by the Finnish Environment Institute SYKE. The WSFS has recently been developed to simulate more detailed spatial variation for basin-scale soil moisture.

In a mining district the spatial resolution of WSFS-Vemala need to be finer to include site-specific variation of soil types, soil surfaces, and vegetation. This enables accurate simulation of soil moisture and evaporation. Furthermore, the description of surface water movements needs to be refined to include an elevation model and the ditch network in the mining district. With these refinements, the WSFS-Vemala would include capabilities for simulation and forecasting of evaporation, soil moisture, runoff, surface water movements, movements of tracer substances (such as oxygen) and groundwater recharge within the mining district. For example, in the case of a spill from the mining district, the WSFS-Vemala can be applied for real time forecasting of the spill transport in rivers and lakes.

WSFS is used for flood forecasting, real-time monitoring, nutrient load simulation, and climate change research. Hydrological water balance maps are created in real time. Forecasts are made on a daily basis for over 500 discharge and water-level observation points. Forecasts are used for lake regulation planning, flood damage prevention, and as information for the public and authorities. (Finnish Environment Institute 2013)

The basic component of a watershed model is a conceptual hydrological model which simulates runoff using precipitation, potential evaporation, and temperature as input (Figure 14). The main components of the hydrological model are precipitation, snow, soil moisture, subsurface, and groundwater models. The WSFS hydrological model consists of small sub-catchments, with an average size of 60 km² (20–500 km²) and numbering over 6,000 in Finland. (Vehviläinen *et al.* 2005)

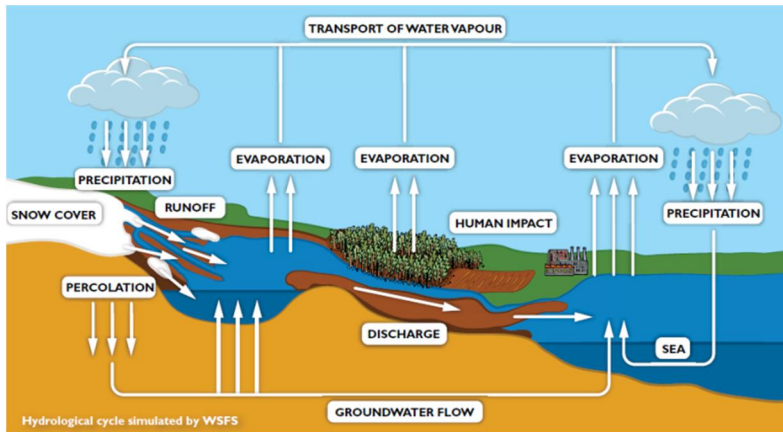


Figure 14. Hydrological cycle simulated by WSFS.

Water balance simulations are conducted for each sub-catchment, and the sub-catchments are connected to produce the water balance and simulate water storage in the river and lake network within the entire catchment. The sub-models in WSFS include a precipitation model calculating a corrected real value and form for precipitation, a snow model based on the temperature-index (degree-day) approach, a rainfall-runoff model with three storages, and models for lake and river routing. WSFS includes approximately 2,600 lakes. The data of the lakes is obtained from Finland's national database compiled by SYKE. The input data for the hydrological model is daily precipitation and air temperature. Potential evapotran-

Water balance modelling tools

- ✓ Spreadsheet, *e.g.* Excel-based deterministic models quite commonly used but can act as dynamic models with a specialized add-in tool
 - ✓ Useful for easy projections, can be rapidly implemented and used to store, display, and check dynamic model inputs, or display and analyze dynamic modelling results
 - ✓ Drawbacks: Not transparent, not very well suited for complex modelling, complex models may be difficult to interpret or explain, add-ins needed for uncertainty assessment, errors
- ✓ Shift from deterministic methods towards dynamic models, that can be coupled to hydrological, geochemical, economic, reactive transport and to chemical equilibrium models
- ✓ Dynamic modelling simulators: Extendable modelling platforms GoldSim, MATLAB Simulink; pre-packaged modelling systems, STELLA, Vensim *etc.*
 - ✓ More versatile, suitable for complex modelling tasks and complex scenarios, more detailed evaluation
- ✓ WSFS – Watershed simulation and forecasting system
 - ✓ WSFS has mainly been used for flood forecasting, real-time monitoring, nutrient load simulation and climate change research

spiration (PET) is calculated in WSFS with an empirical equation that uses air temperature, precipitation, and time of year (an index for available net radiation). This PET routine has been calibrated and verified with observations of potential evaporation data (Class-A). The actual evapotranspiration is calculated as a function of PET and soil moisture deficit produced by the rainfall-runoff routine. WSFS is calibrated against observations of snow water equivalent, extent of snow covered area, lake water level, and discharge. The data used in the calibration were from the Finnish national archive. (Veijalainen 2012)

5.2.2.3 Hydrogeological modelling and groundwater flow modelling

The methods for forecasting groundwater flow directions and velocities can vary from simple hydraulic head interpretation to mathematical groundwater flow and transport modelling. As the simplest methods are not applicable for every case, groundwater flow and transport modelling is needed. A need for a hydrogeological model or a model of the geological structure that takes into account the hydrogeological conditions in both soft sediments and bedrock is crucial in understanding and modelling of the groundwater flow in mining areas.

The groundwater model provides information on water balance analysis, water storage, groundwater flow system, solute and contaminant transports (mine operation area, tailings, water rock pile), and dewatering analysis in the mine pit area. Groundwater modelling with good calibration and validation from the historic observation data is used for the prediction of, for example, change of groundwater storage, recharge and discharge rate as well as potential change of groundwater quality under current and climate change conditions. It is normally used as a support tool for the licensing and permitting of mining operations. The groundwater flow path can be used to predict the potential pathway of the solute and contaminant transport from tailings or mine waste materials which can pose a long-term threat to the groundwater and natural environment. The solute transport model calculates the concentration and movement of dissolved solute in groundwater and it needs the flow path information from the groundwater flow model. Mine water balance models can be useful in managing water resources on a large scale. However, for site-specific areas which contain more complicated groundwater and surface water interactions and complex heterogeneous watershed and aquifer systems, a more sophisticated numerical model is needed that is able to simulate the complex system from the movement of surface water, groundwater recharge, surface leakage and runoff from groundwater flow within the mining district. The numerical models use mathematical approaches to solve the groundwater flow equations in multi-dimensional models (1D, 2D or 3D). The solving equations, such as finite-differences or finite-element methods for hydrogeological modelling and groundwater flow modelling, are available in many computer codes both in the open-source and commercial platforms. The solving of the mathematical equations for the groundwater flow is automated, whereas the modelling of the geological units, *i.e.* the geometry of the flow model, and the parameterization can

be difficult and requires many geological, geophysical and hydrogeological studies and measurements.

Because surface water and groundwater are connected in the hydrological system, the water resources analysis should consider surface and groundwater modelling as a single system. A few modelling codes are able to model the whole watershed area linked from the surface water through to the groundwater systems. However, groundwater-modelling packages usually have extensions for, e.g. the calculation of the flow in unsaturated, partially saturated or in frozen media, and forward and backward particle tracking and calibration. The geometrically accurate and correctly calibrated groundwater flow model can be used to predict the temporal evolution of the groundwater flow and balance in the mining area. Also, changing the geometry and parameterization are very useful when evaluating the groundwater effects of, e.g. the earth-moving and building in mining area. The groundwater flow model can be coupled or used in conjunction with the reactive, multi-component, geochemical modelling software to model the reactive transport of the groundwater. This approach helps to minimize the adverse effects of contaminants transported with groundwater. The groundwater flow, transport and reactive modelling combined into a comprehensive surface water flow model with linking of results both ways provides the water management personnel in mines an invaluable tool for water management.

A number of open sources for public domain (free access) and commercially numerical codes and techniques is available. Each code has potential strengths and weaknesses depending on the specific objectives for which the model is developed. The selection of the modelling code depends mainly on the modelling objectives and characteristics of the mine site and groundwater systems, since different mine sites have different conditions. For example, 3D groundwater flow modelling should be suitable and be built to represent the groundwater flow from all directions in an underground mine or an open pit, while a 2D numerical model can be sufficient for studying two dimensional vertical flow in the waste rock pile irrigation process which allows determination different levels of saturation within the pile. Some commonly used computer codes with good modelling features to simulate the open pits and underground mines exist, and are well accepted for surface water and groundwater flow modelling and solute transport modelling. Additional information on groundwater flow models is available on the internet including a good groundwater modelling summary and guidelines from Wels *et al.* (2012) and Barnett *et al.* (2012).

Data input for modelling

Surface water and groundwater flow modelling can be performed on the regional scale through site-specific modelling. The modelling requires a good understanding of the hydrogeological characteristics of the area and integration of data from multi-disciplinary sources, such as geological, geophysical, spatial and geostatistical. The hydrogeological study should include specific information on:

- Aquifer characteristics, such as extent and thickness of aquifers, confining units, and structural controls
- Hydrological boundaries that control the rate and direction of groundwater movement
- Hydraulic properties of the aquifers and confining units
- Horizontal and vertical distribution of hydraulic head throughout the modelled area for initial conditions, steady-state conditions, and transient conditions where the hydraulic head may vary over time, and
- Distribution and amount of groundwater recharge, pumping or injection of groundwater, and leakage to/from surface water bodies.

Groundwater flow modelling and model calibration should utilize information in a versatile way; for example, data may be measured in the field, analyzed in the laboratory, estimated by experience from similar aquifer systems, or selected arbitrarily from a wide range of possible sources. The data input for the modelling should include (Wels *et al.* 2012, Barnett *et al.* 2012):

- Spatial distribution and temporal variation in groundwater level, piezometric head, flow direction, and flow rate
- Spatial distribution of hydraulic properties such as hydraulic conductivity or transmissivity, porosity, storability, and information on aquifers or aquitards of interest; correlation to lithology, geological structures (*i.e.* faults) or geotechnical parameters (*i.e.* fractures) and measurements that describe the geology of the subsurface to identify aquifer boundaries and modelling area
- Estimates of hydrogeological properties obtained by aquifer tests, slug tests, and permeameter tests on cores
- Geophysical data, including seismic and ground-based or airborne electromagnetic data used to define stratigraphy
- Downhole geophysics leading to understanding of fracture density and orientation
- Records of pumping abstraction and irrigation rates
- Estimates of groundwater recharge and evapotranspiration rates, recharge and discharge zonation
- Measurements of stream base flow, streamflow, or water quality in losing and gaining streams, spring flow, seepage, well discharge, and
- Climate data (such as precipitation, temperature, evaporation), and many other related data. (Wels *et al.* 2012, Barnett *et al.* 2012)

Apart from the data needed for the groundwater flow modelling, additional data for solute transport modelling is required, including (Wels *et al.* 2012):

- Measurements of groundwater quality over time and concentrations of solutes and tracers that could provide insight about flow directions, groundwater age, and/or transport parameters
- Location, history, and mass loading rate of chemical sources and sinks
- Average groundwater velocities (vertical and/or horizontal)
- Effective porosity
- Bulk density and organic content of soil
- Dispersivity (both longitudinal and transverse)
- Reactive transport parameters (laboratory studies may be required). (Wels *et al.* 2012)

MODFLOW

MODFLOW is a 3D finite-difference groundwater flow model developed by USGS (McDonald & Harbaugh 1984, Harbaugh *et al.* 2000, Harbaugh 2005). The code has a modular structure that allows modification for a particular application. Many new capabilities or packages have been added to the original model. MODFLOW simulates steady-state and transient flows in an irregularly shaped flow system in confined, unconfined, or a combination of confined and unconfined (“convertible layer”) aquifers (Wels *et al.* 2012). 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.

The main advantages of MODFLOW are that the code is robust, easy to use, and versatile. It allows the user to extract detailed water balance information (FLOWBUDGET) from the model, which greatly assists with model interpretation (Wels *et al.* 2012). The main limitations of MODFLOW include the inefficient use of rectangular grids to represent complex geometries and convergence problems related to wetting/drying of cells near the water table. If the simulated water table in an uppermost (active) cell in an unconfined (or convertible) layer falls below the bottom elevation of the cell, this cell is classified as dry and inactive. In subsequent iterations, this cell may be made wetted or active again, which can cause significant convergence problems, particularly in steep terrain where the water table may interact with several model layers. This problem is avoided by assuming confined conditions which may be adequate for some situations such as regional study or baseline conditions but can result in significant error in flow predictions in site-specific areas (*e.g.* in inflow to an open pit) (Wels *et al.* 2012).

Simulated 3D flow paths computed from steady-state or transient groundwater flow by MODFLOW can be presented in MODPATH. MODPATH is a particle-

tracking post-processing package which 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. It calculates the path lines 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 the travel times of contaminants. 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 groundwater flow systems. It is also useful for delineating sources of water to discharge sites and aquifers in systems simulated with MODFLOW (Wels *et al.* 2012).

MODFLOW is commonly used in combination with MT3DMS and other codes to simulate solute transport, as well as with MIKE 11 for flow in river and stream networks (Barnett *et al.* 2012). Although MODFLOW is a simulation of saturated flow, the current version of MODFLOW is capable of coupling with particular packages such as VSF (Variably-Saturated Flow) (Thoms *et al.* 2006), UZF1 (Unsaturated-Zone Flow) (Niswonger *et al.* 2006), and HYDRUS-1D (Twarakavi *et al.* 2008) to simulate flow in the unsaturated zone and surface-water groundwater interactions. MODFLOW is recommended to simulate groundwater flow for most water resource assessments, while the more sophisticated codes such as MODFLOW SURFACT or FEFLOW may be suitable for more complex geometry or in steep topography aquifer.

MT3DMS

MT3DMS is a comprehensive 3D numerical model for simulating transport of multiple reactive solutes in complex hydrogeological settings (Zheng & Wang 1999). It is open-source software that can be coupled with MODFLOW to compute coupled flow and transport. MT3DMS has a modular design that permits simulation of transport processes independently or jointly. It is capable of modelling advection in complex steady-state and transient flow fields, anisotropic dispersion, first-order decay and production reactions, as well as linear and nonlinear sorption. MT3DMS is linked with 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 method, 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), and dispersion-dominated problems (FD). (Wels *et al.* 2012)

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 graphical user

interfaces developed for MODFLOW and it is normally used in conjunction with MODFLOW for the simulation of solute transport in natural resources. (Wels *et al.* 2012)

FEFLOW

FEFLOW (Finite Element subsurface FLOW system) is commercial software based on the finite-element method that simulates 3D saturated and unsaturated flows (both steady-state and transient), mass transport (multiple solutes), heat and fluid density-dependent flow in porous and fractured medias with integrated graphic user interfaces (DHI-WASY GmbH 2014, Barnett *et al.* 2012). The main advantages of FEFLOW include the capability to solve different flow and transport problems, flexibility in model discretization, and the formulation of boundary conditions due to use of the finite-element method. These flexibilities can be very useful for the complex flow simulations (for example in mine developments in structurally controlled bedrock, progressive excavation of an open pit, and/or underground mine pits). (Wels *et al.* 2012) However, in steep terrain or topography, the water table crosses model layers and can cause numerical instability or non-convergence. Referring to Wels *et al.* (2012), the limitations of FEFLOW include:

- 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)
- Does not allow pinching out 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 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), and
- The use 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. (Wels *et al.* 2012)

The FEFLOW code is recommended for use in complex natural resource problems in which complex geometries and/or complex boundary conditions will have to be simulated. FEFLOW is also suitable for density-dependent groundwater flow problems (*e.g.* saltwater intrusion, groundwater flow involving brines).

MODFLOW SURFACT

MODFLOW-SURFACT is commercial software developed by Hydrogeologic Inc. (HGL 2014) to simulate 3D unsaturated and saturated groundwater flow and solute transport. It was developed to overcome specific limitations in MODFLOW and MT3DMS, e.g. the drying/wetting problem, enhanced equations for performing unconfined simulations to handle the complete desaturation and resaturation of grid blocks, and accurate delineation and tracking of the water table position in aquifer. Additional improvements offered by the MODFLOW-SURFACT code include the use of a curvilinear grid for efficiently fitting irregular domain geometries, additional boundary conditions (seepage face, unconfined recharge) and adaptive time stepping. (Wels *et al.* 2012) These additional abilities may be of importance in some natural resource projects, in particular where unconfined conditions are encountered in steep terrain or induced by mine dewatering.

HydroGeoSphere (HGS)

The HGS model (Therrien *et al.* 2012) is commercial software based on a 3D control-volume finite element method that is designed to simulate the entire terrestrial hydrologic system consisting of surface and subsurface flow regimes. The model simulates unsaturated and saturated flow, mass and heat transports, and provides a complete water and solute balance. It uses a globally implicit approach to simultaneously solve the 2D diffusive-wave equation and the 3D form of Richards' equation in solving the variably saturated flow continuously across both the unsaturated and saturated zone. HGS also dynamically integrates key components of the hydrological cycle such as evaporation from bare soil and water bodies, vegetation-dependent transpiration with root uptake, snowmelt, and soil freeze/thaw. Features such as macro pores, fractures, and tile drains can either be incorporated discretely or using a dual-porosity, dual permeability formulation. HGS is especially well-suited for highly integrated hydrological modelling involving detailed simulation of rainfall, runoff, infiltration, vadose zone flow, streamflow, and groundwater processes. For the transport of pollutants in groundwater, HGS provides a comprehensive transport-modelling capability by integrating transport across the surface water – vadose zone – groundwater continuum as a whole system. Hence, boundary conditions are defined around the integrated components of these systems rather than having individual models, and it does not need to provide for a wide range of sub-modules to specifically deal with the surrounding boundary conditions, for example the groundwater system, representing certain hydrological conditions. It is also capable of simulating heat transfers and variable density (e.g. saline water) flow. In the saturated and unsaturated zone, it can handle flows in fractures, macropores, and porous media. However, the simulation in the unsaturated zone in HGS is solved using the 3D Richards' equation and it requires generally very fine grids for accurate solutions and short time steps. For simulations of large groundwater basins, such a resolution is largely impractical and computationally time-consuming. Furthermore, due to the implicit complex-

ity of HGS, the simulation and calibration processes with HGS may need significantly more CPU time and resources than other groundwater models, e.g. MODFLOW. (Harter & Morel-Seytoux 2013)

5.2.2.4 Equilibrium and chemical models

Chemical equilibrium and reaction modules can be implemented into the model software programs currently on the market and this work has been started in some parts of the world. The chemical equilibrium and hydrothermal chemical modules in the water management software enable the model to take into account the interactions between the components in the various media, for example, rainwater filtrating through the soil or through fractures in the rock of certain composition in addition to reactions occurring when waters and waste-waters of different consistencies converge.

HSC

HSC is a versatile chemical, thermodynamic and mineral processing software package whose first module was created in 1974 to calculate equilibrium compositions in the Outokumpu Oyj sulphur plant gas line. Thermodynamic equilibrium calculations are performed with the enthalpy (**H**), entropy (**S**) and specific heat capacity (**Cp**) of the chemical compounds and constituents taking part in the chemical reactions. The HSC digital database replaces the laborious phase of collecting reliable data and experimental results from literature and scientific articles. The HSC software was primarily used as an internal tool, and later in 1987 it was released to other companies. The ownership of HSC was transferred to Outotec Oyj in 2006, the company founded based on Outokumpu Oyj technology. The current HSC version 9.0 contains 24 calculation modules. (Figure 15)

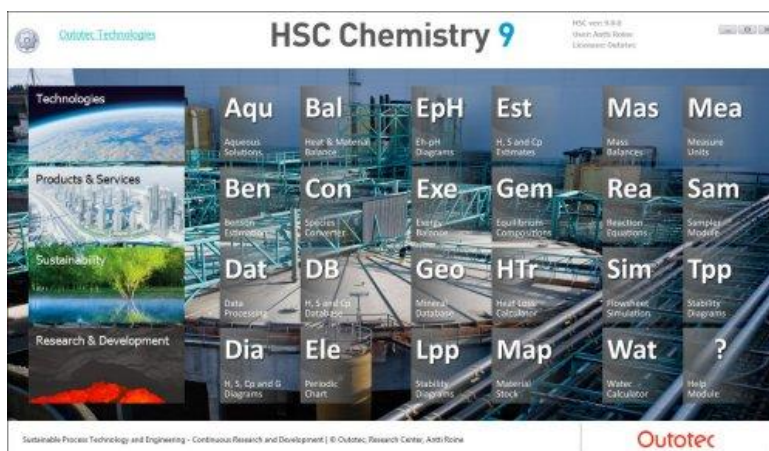


Figure 15. HSC user interface (Outotec Oyj 2016).

HSC Chemistry is the chemical reaction and equilibrium software for performing thermodynamic calculations in scientific education, industry and research. HSC Chemistry allows making calculations and studying the effects of different variables on a chemical system at equilibrium. Given the amounts of raw materials and conditions, the program will calculate the amounts of products. HSC also makes heat and material balance calculations as well as Eh-pH-diagrams allowing the dissolution and corrosion behaviour of different materials to be studied. However, HSC does not take into account the kinetics of the chemical reactions.

The HSC Sim module expands the traditional HSC Chemistry software by enabling it to apply to the whole process made of several process units and streams, as shown in Figure 16. The HSC Sim module will consist of graphical flowsheet and spreadsheet type process unit models. The process units will be created to contain the variables specific to the case, be it chemistry, metallurgy, or mineralogy, *etc.* where each unit is one Excel file. The process model is built from the process units and can be reused in other process simulations.

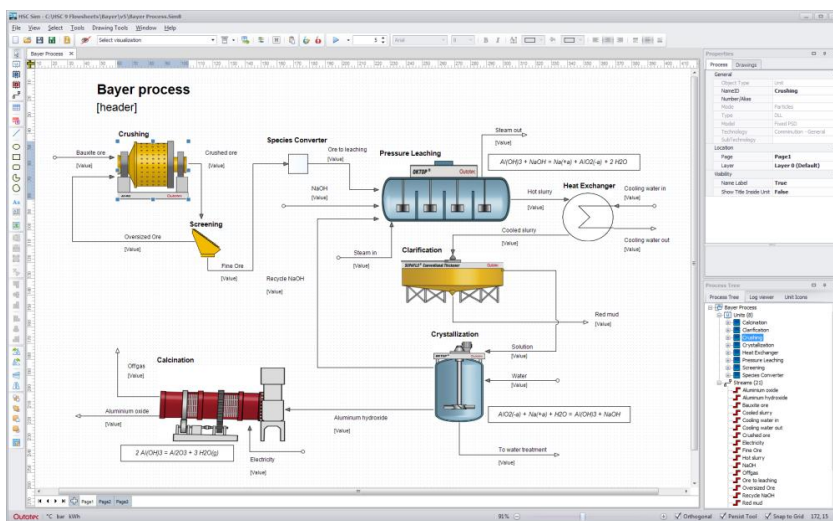


Figure 16. HSC Sim process simulation of Bayer process (Outotec Oyj 2016).

HSC Sim is used to model the refinery process. During the planning and feasibility studies of the refinery process, HSC Sim is a valuable tool in planning the process, studying the effect of parameter variations, and making risk analyses. The water management program of a mine site needs the information given by HSC Sim on the composition of the water flowing out of the refinery plant, the wastewater. The refinery process itself can be considered to be a black box that is modelled by HSC Sim and sends a stream of certain composition to the mine site water treatment process. HSC Sim is to be used in making risk analyses and variation testing of the water treatment process on the mine site as the refining

process changes due to changes in process or raw material. This is very valuable information for the water treatment program.

OLI

OLI is an electrolyte simulation software tool that can be linked to process simulation programs, either commercial software programs such as Aspen Plus from AspenTech, UniSim Design from Honeywell, SimSci PRO/II from Schneider Electric, or to a company proprietary spreadsheet. OLI software is used to model multicomponent, multiphase aqueous systems, to predict thermodynamic properties such as enthalpy, entropy, heat capacity, volume, equilibrium constants and activity coefficients. As electrolyte solutions are its strongest field, its particular features include predictions of pH, osmotic pressure and oxidation-reduction potentials as well as surface tension and interfacial tension. Redox chemistry can be performed for alloys as well as pure elements.

The OLI product portfolio contains the following: OLI Stream Analyzer which is the base product of the OLI family and allows in-depth studies of electrolyte chemistry, e.g. temperature, pressure, pH and composition studies for simple mixes and splits; OLI Corrosion Analyzer which contains, e.g. real-solution Pourbaix Diagrams and Stability Diagrams, (chemical) kinetic rates of corrosion model, and localized corrosion indicators, and OLI ScaleChem which is an add-on product that centres on mineral scale prediction for oil and gas production scenarios.

The OLI Aqueous (AQ) model is based on comprehensive aqueous speciation, a predictive Equation of State (EOS) for standard-state properties (Helgeson-Kirkham-Flowers EOS), an activity coefficient model and convergence heuristics. The model is based on published experimental data. Data regressions, estimation and extrapolation are used when required. The AQ model gives accurate predictions for concentrations of 0 to 30 molal. OLI's Mixed Solvent Electrolyte (MSE) Model extends the limits from infinite dilution to the molten salt limit.

For the mine-site water management program, OLI is a software tool that can be used in modelling the concentration plant for cases where the process simulation is performed with OLI's alliance partners' simulation software or in the case of proprietary simulation software. OLI's strongest competence is in the high-molality electrolyte solutions and corrosion studies, but as it is reported to give accurate predictions also at infinite dilutions, the reactions occurring in the mine-site's tailings ponds and environmental water sources can be modelled with OLI. (OLI software 2016)

ChemSheet

ChemSheet is an advanced thermochemical simulation tool which combines the flexibility and practicality of spreadsheet operations with rigorous, multi-phase thermodynamic calculations. ChemSheet software was invented and developed by VTT and in 1999 commercialized in collaboration with the German SME GTT

Technologies GmbH which markets and distributes thermodynamic calculation software and databases worldwide.

ChemSheet calculation software is based on the constrained Gibbs energy minimization method (Constrained Free Energy, CFE method). The user interface is Excel worksheet into which the customer's application is defined and set up. ChemSheet simulations are run directly on the spreadsheet and the functional and graphical features of Excel can be used.

In comparison to other software, ChemSheet's thermodynamic free energy can be generalized for systems subdued to physical or dynamic work factors, meaning that it is possible to handle both time-dependent kinetics and various physical constraints in the classical thermodynamic calculation routines. This has broadened the scope of cases that ChemSheet calculations can model. The array of applications that ChemSheet has been applied to include high-temperature systems, biochemical systems, materials chemistry, corrosion, industrial reactor scale-up and process simulation. Practical models and expert systems have been developed, *e.g.* in the chemical industry, pulp and paper, cement and lime manufacturing, metallurgy, steelmaking, power production and environmental technologies. (Koukkari 2009, VTT 2014)

ChemSheet can be applied to many of the questions arising in the mine site water management program, especially in the water sources and reservoirs on the mine site. Because the composition and physical conditions of the waters vary due to changes in wastewater from the concentration plant and weather changes, the reactions occurring amongst the constituents in *e.g.* tailings ponds change. ChemSheet can be used to perform risk analyses of the possible reactions in the water sites or in connection with online monitoring of the species in the pond, and it can give real-time information of what is occurring in the reservoirs, ponds, and ditches, *etc.*

PHREEQC

The PHREEQC geochemical model (Parkhurst & Appelo 2013) is a computer program for simulating chemical reactions and transport processes in natural or contaminated water. PHREEQC stands for **PH** REdox **E**quilibrium (in **C** language) and is widely used public domain geochemical modelling software available from USGS. It is available for free downloading from the USGS website. PHREEQC has capabilities for:

- Speciation of water analysis and saturation-index calculations
- Batch-reaction and 1D transport calculations with reversible and irreversible reactions, which include aqueous, mineral, gas, solid-solution, surface-complexation, and ion-exchange equilibria, and specified mole transfers of reactants, kinetically controlled reactions, the mixing of solutions, and pressure and temperature changes, and

- Inverse modelling, which finds sets of mineral and gas mole transfers that account for differences in composition between waters within specified compositional uncertainty limits.

PHREEQC has been applied in geochemical modelling for mine water management studies around the world. PHREEQC can be used to assess the degree and type of contamination of the aquifer resulting from mixing of mine waters and aquifer waters. With information on the groundwater flow rate of the contaminating mine-water mine and good calibration with real data, it has been shown that the modelling can accurately predict the contaminated aquifer.

PHAST

PHAST (**PHREEQC And HST3D**), version 2, is a program for simulating multi-component, reactive transport of solutes in 3D saturated groundwater flow systems. Not only can PHAST be used to simulate groundwater flow and solute transport, but also to model equilibrium and kinetic geochemical reactions. PHREEQC is embedded in PHAST, which enables the simulation of a wide range of geochemical reactions. The modified version of the finite difference code HST3D is responsible for modelling groundwater flow and transport in PHAST. (Parkhurst *et al.* 2010)

PHAST can be used to study both natural and contaminated groundwater systems of different scales. Studies concerning the migration of inorganic and organic contaminants, nutrients, and radionuclides, aquifer storage and recovery or remediation projects, and natural rock/water interactions in aquifers can be performed using PHAST. However, it is not suitable for simulating unsaturated-zone, multi-phase, or density-dependent flows. (Parkhurst *et al.* 2010)

TOUGHREACT

Thermo-hydro-geochemical processes can be simulated using TOUGHREACT, in which the calculation of geochemical reactions is coupled with the TOUGH2 v2 code. TOUGH2 simulates non-isothermal multi-component transport, fluid flow and heat flow. Thermodynamic databases from other codes, such as EQ3/6 or PHREEQC, can be used for geochemical modelling. (Xu *et al.* 2012)

TOUGHREACT can be applied to solve many kinds of problems concerning reactive fluid and geochemical transport, such as contaminant transport, evolution of natural groundwater chemistry, geological storage of CO₂ in deep formations, mineral deposition, alteration and silica scaling in hydrothermal systems, environmental remediation, and biogeochemical transport. (Xu *et al.* 2012)

HYDRUS 2D/3D

HYDRUS 2D/3D is software for analyzing water flow and solute transport in variably saturated porous media. The simulation of 2D and 3D movement of water, heat, and multiple solutes in fluctuating saturated media is based on finite element

modelling. A parameter optimization algorithm is included in HYDRUS for inverse estimation of parameters for soil hydraulic transport and/or solute transport. HYDRUS contains an interactive graphical user interface. (Integrated GroundWater Modeling Center 2015)

HYDRUS 2D can be coupled with PHREEQC to create a versatile simulation tool HP2, in which transient water flow, multiple component transport, mixed equilibrium or kinetic biogeochemical reactions, and heat transport in 2D variably saturated porous media can be simulated. In addition to its capability to simulate 2D variably saturated water flow and advection-dispersion type equations for heat and solute transport, HP2 is also able to simulate biogeochemical reactions in water, vadose zone and in groundwater systems that occur at low temperatures, including those mineral, gas, exchanger and sorption surface interactions that are based on thermodynamic equilibrium reactions, kinetic reactions, or mixed equilibrium-kinetic reactions. (Integrated GroundWater Modeling Center 2015)

5.3 Case examples

5.3.1 Comprehensive water management solutions

Only very few case examples representing mine water management practices that are comprehensively well implemented can be found in the literature. The Chilean Copper Commission (COCHILCO) published a report in 2008 called *“Best Practices and Efficient Use of Water in the Mining Industry”*, which contains six short case-study examples with different approaches to those water management issues that are important for the Chilean mining industry. Two cases in this report (Candelaria Mine and Los Pelambres Mine) have the title *“Efficient and sustainable management of the water resource”* and may be worth reading. (Chilean Copper Commission 2008) Also the report *“Water Resource Management and the Mining Industry”* by the Brazilian National Water Agency, Ministry of the Environment and Brazilian Mining Association (2013) describes nine case studies of the integration of water resource and mining management. However, these cases seem to be rather old.

In general, it is also noteworthy that the few cases reported seem to be almost exclusively located in the water shortage areas. Thus, as the challenges in Finnish mine water management concern water surplus, the educational offering of these cases is not very rich. Due to the lack of good examples available, only three case studies are

Other modelling tools

- ✓ Hydrogeological and groundwater flow models
 - ✓ MODFLOW, MT3DMS, FEFLOW, MODFLOW SURFACT, HydroGeoSphere (HGS), PHREEQC
- ✓ Equilibrium and chemical models
 - ✓ HSC Sim, PHAST; PHREEQC, TOUGHREACT, HYDRUS 2D/3D, Chem-Sheet, OLI

presented in the following sections. These cases are selected to represent different approaches to water management. The first case, Ulan Coal Mine, seems to have quite a comprehensive water management program that is described in detail. For example, the company has published their environmental management strategy on the Internet containing a water management plan for the mine complex. In addition, the results from surface water monitoring, groundwater monitoring and water balance modelling among many other monitoring results are presented in their annual environmental review. Also predictive water balances are modelled and reported. The second case, Casino project is not yet an operative mine, but acts as an example of performing water management actions already in the planning phase of the mine project. The whole project proposal is available online, but in this text the focus is put on the modelling aspects. In addition, the planned Casino mine was one of the few case examples reported and found that is located in climate conditions somewhat similar to Finland. The final case, Antamina mine, is an example of water management at alternating climate conditions.

Again, it should be noticed that the current level of water management in Finnish mines is presented in Appendix. As can be seen in the Appendix, some of the Finnish mines represent the state-of-the-art in water management quite well.

5.3.1.1 Ulan Coal

The Ulan Coal Mine Complex operated by Ulan Coal Mines Limited is situated in the Western Coalfields of New South Wales, Australia and covers an area of approximately 17,959 hectares. The complex is located at the headwaters of two river catchments and comprises an underground mine currently in operation, another one under construction, and an open pit. The operations are owned and/or managed by Xstrata Coal NSW. (Glencore 2014a)

According to the company, all operations at the mine complex comply with the requirements given in their environmental management strategy. When the strategy is followed, an effective, consistent and continually improving environmental and community management can be achieved and the statutory requirements fulfilled. The environmental management strategy is also the basis for development of sustainable development management system. The strategy describes the means for efficient communication, planning, documentation, regular monitoring, evaluation, and the review and feedback processes. The water management plan, which contains thorough surface water and groundwater response plans, a surface water monitoring program and a groundwater monitoring program, is included in the strategy. (Glencore 2014a) Some facts of the Ulan mine water management system are listed below:

- The most important water sources for the mine complex include precipitation into the area of open pit and dirty water catchments, and groundwater inflows to the underground mine.

- Most water flows from both mining areas are directed to the water management system although some waters from the open pit area may end up in the groundwater.
- Waters in the mine water management system are used and reused efficiently in mining operations.
- Underground voids are main water storages. Also the East Pit is an important water storage area.
- Coal handling and preparation plant, dust suppression and evaporation are the main water losses/demands.
- Surplus waters are either discharged after treatment or used within the irrigation scheme.
- Rowans Dam, Bobadeen Dam, East Pit and underground storage areas are the most important infrastructure components in the mine water management system. (Umwelt Pty Limited 2009)

As a whole, the mine water management system in Ulan Coal Mines Complex includes dewatering systems, water storages, irrigation scheme, water treatment facility, retention and sedimentation basins, settlings and tailings ponds, drainage ditches, laydown hardstand areas, fuelling areas as well as levee banks and earth bunding constructed around the main stockpiles. The aim of the water management system is to prevent contamination of fresh waters, reduce discharge of pollutants into the surrounding environment, minimize harmful effects to the natural water sources nearby, manage approved discharges to meet licence conditions, segregate waters of different qualities to minimize the need for water recycling and treatment, and manage water volumes on the site to meet operational requirements. (Glencore 2014b)

The surface water monitoring program of the complex consists of the integrated monitoring strategy aiming to measure and define changes in stream health and channel stability caused by the mining activities, and to establish the monitoring and reporting requirements in a way that water quality and quantity trends can be reported against the Environmental Protection Licence conditions. Both surface monitoring points and discharge monitoring points are placed on the site. For example, nine surface water monitoring points monitoring the pH, EC, TSS, TDS or turbidity by monthly grab samples, and two monitoring points monitoring the TSS by monthly grab samples and the pH and EC continuously, are located within and outside the mine complex. (Glencore 2014b)

Based on the results of the groundwater monitoring program, trends in groundwater levels can be observed, groundwater depressurization, and associated inflows of groundwater against modelled scenarios can be estimated, and possible impacts on private bores in proximity of the mine area determined. For example, the North Monitoring Network consists of 54 environmental monitoring bores for groundwater level and quality monitoring within and outside the mine area. The monitoring equipment comprises standpipe and vibrating wire piezometers.

Groundwater level monitoring using standpipes is performed four times per year. The pH and EC are measured two times per year from certain standpipe piezometers and broader groundwater chemistry is monitored once a year. Four standpipes are located close to the underground mine and thus equipped with automatic water level recorders. Also, three continuous vibrating wire piezometers are located in the North Monitoring Network, and the company aimed to install three more in 2014. (Glencore 2014b)

A revised reporting water balance model used to determine monthly balances was originally developed in 2007. The model is a spreadsheet-based program that uses Microsoft Excel as a modelling platform. Predictive water balance calculations reaching to the year 2029 have been performed with the help of @Risk software using the Monte Carlo analysis method and are presented together with the reporting water balance model in the report called "*Ulan Coal – Continued Operations Surface Water Assessment*" by Umwelt Pty Limited (2009). Also the current monitoring and reporting of the site-wide balance is based on this same work and the groundwater modelling that was performed in 2010 (Ulan Coal Mines Limited 2011).

According to the company's water management plan, the site-wide water balance should be reviewed and reported on a yearly basis and managed on a three-yearly basis. After the period of two years the following list of actions needed to be undertaken (Ulan Coal Mines Limited 2011):

- Groundwater monitoring results vs. the groundwater predictions reviewed
- Groundwater model recalibration made when necessary, and
- Based on the model recalibration and the mine plans for the next five-year period, a predictive water balance for the next two years prepared, including rainfall yield modelling and water loss modelling data. (Ulan Coal Mines Limited 2011)

An assessment of the current water discharge strategy should also be included in the two-yearly review of site water balance to confirm that it is at the same level as the discharge requirements of the site-wide balance. Also the capacity of the water management system to withstand future discharges should be stated on the basis of the assessment. (Ulan Coal Mines Limited 2011)

The site-wide water balance model contains several modules representing the catchments and main components of the water management system in the mine, including water sources (consisting of precipitation, groundwater and drinking water), water demands, water losses, changes in water storages onsite and water discharges/transfers off site. All these factors are more accurately identified and characterized in the company's water management plan. (Ulan Coal Mines Limited 2011) The site water balance broken down into smaller balances enables assessment of water movement around the site in more detail. Overall water inputs and outputs can be analyzed after summing up all components. Over recent years, the model has been continually improved as the knowledge of water movement on site has increased. The balance is updated two times per year.

(Glencore 2014c) Three different data types are included in the water balance calculations *i.e.*, data from on-site monitoring, meteorological data and coal-processing data (Ulan Coal Mines Limited 2011).

5.3.1.2 Casino project

The Casino project represents an example of the early planning of water management issues. The Casino mine will be located in west-central Yukon, Canada. The project is currently under the environmental permitting and licensing phase; the mine is planned to be fully operational in 2019. The mine will be an open pit and located in a region of discontinuous permafrost. In addition, ore stockpiles, a plant site, a heap leach facility, and a tailings management facility are planned to be located on the site. The deposit in the Yukon area contains copper, gold, molybdenum and silver, and Casino is one of the largest of the many porphyry copper deposits in the world. According to the plans, a copper/gold concentrate, a molybdenum concentrate, and gold/silver doré bars will be produced for sale. Once in operation, around 120,000 tonnes of ore will be processed in the mill per day. The estimated operational life of the mine is around 22 years. (Casino Mining Corporation 2015)

Water issues, among many others, are widely discussed in the project proposal. The proposal, containing altogether around 7,000 pages of documents (CBC News 2014), was submitted in January 2014, and includes sections in which issues related to water quality assessment, water and sediment quality baseline studies, hydrology and hydrogeology baseline studies, geochemical studies, numerical groundwater modelling, water balance modelling, and water quality modelling are discussed. The plan for overall water management of the Casino project is also presented. The strategy for water management introduced in the plan has been incorporated into the water balance. (Casino Mining Corporation 2015)

The water balance model developed for Casino integrates clean waters and wastewaters, as groundwaters, surface waters, and mine water operations are included in the model. The model was created for evaluating the flow and quantity of waters around the proposed site, in the ground, in streams and at different facilities. The model also offers a platform for water quality modelling. Nine different sampling points within the planned mining area were used to collect baseline hydrological and water quality data. (Casino Mining Corporation 2015)

The water balance model includes the following project components: open pit, mill site, tailings and waste rock management facilities, water management and winter seepage mitigation ponds, cyclone sand plant, heap leach facility, and gold ore and low-grade ore stockpiles. The water balance from pre-production to post-closure phases of the proposed mine was modelled using GoldSim. Average monthly hydro-meteorological conditions were used as a base for the model, and these conditions repeated annually over the whole mine life cycle. The watershed model, numerical groundwater model, and feasibility level operational water balance model developed for the project were integrated into the GoldSim model to be able to evaluate surface water and groundwater flow patterns and operational

flows. The watershed model was used to determine climate conditions prevailing in the area, and the numerical groundwater model provided information on groundwater flow paths and magnitudes. The operational water balance model together with the project's feasibility design were used to create methodologies for operational water management and production. (Casino Mining Corporation 2015)

The whole life cycle of the mine is estimated to cover over 200 years, and contain the following time points and actions presented in Table 4 (Casino Mining Corporation 2015).

Table 4. The planned life cycle of the Casino project and actions performed in the different phases (Casino Mining Corporation 2015).

Phase	Years	Actions
Pre-operational	8–5	Baseline conditions
	4–1	Pre-production
Operational	1–22	Operation
Post-operational	23–30	Active water management (phase I)
	31–113	Passive water management after discharge from the tailings management facility (prior to discharge from pit lake) (phase II)
	114–220	Passive water management after discharge from the pit lake (phase III)

The water management plan covers the construction, operations and closure phases (phases I to III) of the proposed Casino mine and describes prospective water management and controlling actions in and around the mine area during these phases. All key facilities are covered. The aim of the water management actions is to provide suitable waters for use in ore processing, and to minimize the possible occurrence of harmful environmental effects on water quality downstream and mine structure damage caused by storm flows. The objective of the water control actions is to minimize erosion in constructed areas and to inhibit the access of sediment-laden waters to the receiving environment. The water management strategy includes two different approaches: the operational water management strategy, and the strategies for sediment and erosion control. (Casino Mining Corporation 2015)

Data on hydro-meteorological parameters, such as baseline net precipitation and operations net precipitation, was obtained from a spreadsheet-based (Microsoft Excel) watershed model developed to estimate components of the watershed water balance and represent hydrological conditions during the operational phase. The proposed site was divided into eight sub-catchments, which were separately modelled. In addition, information on monthly mean lake evaporation was used as an input for water balance modelling. However, evaporation was not calculated from the watershed model, but was obtained from the baseline climate report. The aims of the watershed model were to (Casino Mining Corporation 2015):

- Enhance comprehension on baseline hydrogeological and hydrologic conditions in and around the proposed site
- Determine groundwater flow regime that can be used to develop a numerical groundwater flow model
- Define local baseline conditions for surface waters and groundwaters that are usable as reference when assessing the occurrence of potential environmental impacts
- Determine mean net precipitation values on monthly level on key facilities on site to generate information for stochastic modelling in the mine operations water balance model, and
- Generate data on rates of runoff and infiltration for the needs of geochemical source term modelling. (Casino Mining Corporation 2015)

To assess the potential effects of the mining on hydrogeological conditions at different phases of the Casino project and to represent baseline groundwater conditions, a series of groundwater models were developed. MODFLOW-SURFACT was used to develop a 3D steady-state, regional-scale numerical model for years 4, 10, 19, 22 as well as the post-closure phase. Baseline information was used to calibrate the model, which was then modified to include the following facilities: heap leach facility, open pit, tailings management facility, as well as ore and low-grade ore stockpiles in order to assess hydrogeological conditions during operations. The integration of a groundwater numerical model into the water balance generated the following information (Casino Mining Corporation 2015):

- Inflow of groundwater and seepage rates from different components of the tailings management facility
- Rates of groundwater inflow to the pit during operational phase dewatering actions and seepage from the pit lake, and
- Possible pathways of groundwater flow from the main mine components to the tailings management facility, pit and environment. (Casino Mining Corporation 2015).

In addition, a site-wide water quality model was developed to assess discharge water quality in the receiving environment, and to help select water quality mitigation actions. A mass load balance was developed to estimate the contaminant transport rate within the water management system in the receiving waters. The water quality model was fully integrated with the water balance model, as it was built within the GoldSim platform. Six different components were included in the site-wide water quality model: open pit lake, drainage from ore stockpile, heap leach facility, tailings pond and treatment wetlands, seepage management pond, and receiving environment. In the model development, average monthly environmental conditions were used. The simulation timeline used covered 200 years; altogether 29 different water quality parameters were included in the model.

PHREEQC software with dynamic link library element was used to combine geochemical data into GoldSim water quality model. (Casino Mining Corporation 2015)

5.3.1.3 Antamina mine

Antamina mine is located in the Peruvian Andes, approximately 4,200 m above sea level and around 270 km northeast of Lima (e.g. Brown *et al.* 2006, Strand *et al.* 2010, Tuff *et al.* 2015). The mine produces copper, zinc, molybdenum, silver and lead concentrates, and is among the world's top ten producers of both copper and zinc (Antamina S.A Mining Company 2015). Full production at Antamina was reached in 2001 (Brown *et al.* 2006), and according to different estimates, the operational phase will last until 2024–2029 (Brown *et al.* 2006, Antamina S.A Mining Company 2015).

Key features in the Antamina mine site include an open pit, a tailings dam and a pond, two waste rock dumps, a freshwater reservoir, a concentrator plant, a diversion system with multiple routing options, and a slurry pipeline (Keizur 2003, Strand *et al.* 2010, Antamina S.A Mining Company 2015, Tuff *et al.* 2015). The tailings dam of Antamina is in fact the tallest existing tailings dam, and it is designed to withstand difficult circumstances, e.g. exceptionally heavy rains. 98.5% of wastewater derived from the concentrator is recirculated from the dam. (Antamina S.A Mining Company 2015)

The principle of Antamina's water management is to use water resources in a responsible way, meaning that the company follows all national water quality standards, has established controls to fulfil international standards, reuses waters, and monitors water qualities (Antamina S.A Mining Company 2015). The aims of the water management are to:

- Ensure that the capacity of the tailings pond is high enough to handle probable maximum flood;
- Guarantee that a suitable amount of water is available for operations also during droughts;
- Make sure that riparian flow downstream of the tailings area is at an acceptable level, and
- Secure adequate fresh-water resources for use in operations and as service water. (Voss & Letient 2006)

A GoldSim model to assist water management in Antamina was developed in 2002 (Keizur 2003). The concentrator (operational conditions), tailings pond, three other storage ponds, diversion ditches and receiving waters (balance at the site), the precipitation, evaporation and runoff (climate conditions), and the regulatory guidelines (compliance conditions) were the key components or subsystems integrated into the model (Keizur & Manrique Arce 2006, GoldSim Technology Group 2015). In addition to the water balance model, also simple mass balance and

tailings production models were included in the same GoldSim model. Before the use of GoldSim, the water and mass balances were modelled using spreadsheets. These spreadsheet models were used as an input in the development of dynamic modelling. (Keizur 2003) The objectives for the GoldSim model were to:

- Create and establish the water balance for the tailings pond, and perform testing under different climatic and operational circumstances, e.g. to have information on water amount, level, and flow rate for the tailings dam, main dams upstream, as well as the water systems downstream in short to long-term timescale, and
- Support operational decision making. (Keizur & Manrique Arce 2006)

The model is run on a regular basis to help planning and operation of the water management actions (Keizur & Manrique Arce 2006). The modelling results also give mine personnel a tool to evaluate the possible impacts of operational changes on the environment (GoldSim Technology Group 2015).

The model contains user dashboards to simplify its use. With these dashboards, it is possible to define initial conditions and operational scenarios to simulate the performance of the mine system over a given period of time. (GoldSim Technology Group 2015, Voss & Lentin 2006) It is also possible to connect to relational databases on the site, which enables making real-time data simulations. Possible water quality deterioration or violations in minimum instream flow in the river to which water is released from the tailings pond under differing climate circumstances are of primary concern. (GoldSim Technology Group 2015)

Wet and dry seasons are alternating in Antamina (Voss & Letient 2006), and because the company has actively aimed to manage water-originated impacts, the water management infrastructure of the mine is versatile. For example, diversion channels for clean waters, routing systems to dilute contaminated waters, returning system for downstream flows that are not clean enough, and treatment systems or mechanisms for potential discharges (e.g. wetlands, flocculation and neutralization) are in use. Regular monitoring of water quantity and quality in and around the mine site is performed and completed with an extensive geochemical testing program. (Strand *et al.* 2010, Tuff *et al.* 2015) Surface water sampling at various locations is routinely performed. Flow rates and water quality parameters are monitored at least four times per year to obtain information on seasonal variations. (Strand *et al.* 2010) The geochemical studies include laboratory tests, field tests, operational monitoring of the waste rocks, and modelling of the water quality. The purpose of these studies is to increase the knowledge of the environmental effects that may result from the operations and post-closure of the mine, to help identify and implement prevention or mitigation actions, and to revise and develop waste rock and water management programs. (Brown *et al.* 2006) For the needs of mine closure planning, the integration of water balance and water quality models in GoldSim provides knowledge of both water flows and concentrations, which is a requirement when planning a mine in an environmentally acceptable manner. The geochemical model to identify occurrence of the expected geochemical reac-

tions was developed using PHREEQC and Geochemists Workbench. Based on the modelling results, also the most important geochemical mechanisms (such as pH determination and acid generation and neutralization) have been added into the model. As the nature of the model is predictive, it has been used to assess four different closure water management options. (Strand *et al.* 2010)

5.3.2 Equilibrium and chemical models

Modelling of surface water and groundwater flow, infiltration in vadose zone, geochemistry and water balance have been used as assessment tools for mine water management in many mining areas around the world in different mine life cycle phases. Also the integration of groundwater flow models, surface water models, and geochemical models have been used for the assessment and prediction of the hydrogeological characteristics of many mine sites. The following section gives five short examples of the use of equilibrium and chemical models in mining.

5.3.2.1 Hannukainen

Integration of the 3D groundwater flow MODFLOW model, surface water catchment model, and PHREEQC geochemical model was used to assess the hydrogeological baseline conditions at Hannukainen, an iron-copper-gold project in northern Finland. Modelling was exploited at the pre-feasibility phase to predict the potential impacts of mining activities in different phases from operation through to closure. (Lyle *et al.* 2013)

5.3.2.2 Blackfoot Bridge and Henry phosphate mines

The Blackfoot Bridge and Henry phosphate mines are situated in south-east Idaho, USA. Conceptual and 3D groundwater flow modelling based on geological, hydrogeological, groundwater, seepage and spring monitoring data were developed for the mines as tools to understand potential groundwater contamination in the mining areas. (U.S. Department of the Interior 2011)

5.3.2.3 Prosperity Gold-Copper Project

The Prosperity Gold-Copper Project is located in south-central British Columbia, Canada, approximately 125 km south-west of Williams Lake. Groundwater flow models were used to assess the impact of the mining project on groundwaters and surface waters in the catchment area. Available baseline information was used to develop a conceptual model of the groundwater flow regime. After the model was calibrated, it was used to predict the impact of the mining project on the groundwater system. This 3D groundwater flow model was used to assess the impacts of the project. The simulated effects of main facilities on groundwater elevations were used to represent these impacts. (Taseko Mines 2011) The 3D transient

MODFLOW model and 3D transport model MT3DMS were used to predict the pit inflow, stream base flow, and seepage from tailings storage facilities into nearby streams and lakes. Also the impacts of climate change on surface water and groundwater seepage in the long term were studied. (Wels *et al.* 2012)

5.3.2.4 Rosemont copper mine Project

The Rosemont copper mine Project, is located in the northern Santa Rita Mountains, USA. In this project, Myers (2008) used the 3D steady-state groundwater flow model MODFLOW to evaluate the potential impacts of constructing the proposed open pit mine on the hydrogeology, including surface water and groundwater flows on the site and downstream watersheds around the mining area. The model was developed to calculate the water balance, and it also included an estimate of recharge to and discharge from the system. The results from simulations were used to study the flow pattern to be able to predict the effects of dewatering of the proposed open pit on the water balance in the catchment areas.

5.3.2.5 Rum Jungle uranium historical mine site

Rum Jungle is a historical uranium mine site in the Northern Territory, Australia. The site has suffered from environmental issues due to the occurrence of acid mine drainage causing heavy metal mobilization from waste rock, tailings and open pits. Significant environmental impacts on the groundwaters and surface waters have been detected, the East Finnis River as an example. Due to this, a new rehabilitation plan containing a well-monitoring network was developed. A 3D groundwater flow model was also created for the site in order to explain historical and current groundwater contamination on and off site to estimate seepage from different mine waste units (e.g. waste rock dumps, backfilled open pits, Cu heap leach), and to estimate metal loading from different mine waste units to surface water (East Finnis River). The monitoring results have significantly improved the understanding of the extent of acid drainage impact, and the current groundwater quality conditions at the mine site. (Ferguson *et al.* 2011)

6. Water management procedures

In this chapter, water management procedures required for the different phases of the mine life cycle are presented with respect to the most important legislation in Finland. Also mining legislation at the European level is briefly discussed. In addition, as mining nowadays has to be implemented in a socially sustainable and acceptable way, the importance of communicational aspects and community relations pertaining to mining are also highlighted.

6.1 Mining legislation in Finland

Mining activities differ from other industries, for example, due to their long start up process; it can take even decades from ore prospecting work to mine operation. Legislation through acts and decrees governs the activities of a mining project. Mining is very precisely regulated and licensed within the different phases of the life cycle and several administrative permit processes or comparable procedures are required to further the mining project towards the actual mining activities. (Kauppila *et al.* 2011, Ministry of the Environment 2014)

Mining in Finland is restricted by dozens of different acts and decrees; the new Mining Act (621/2011) and the Environmental Protection Act (527/2014) being the most important ones. Also the Water Act (587/2011) and the Act on Environmental Impact Assessment (EIA) Procedure (468/1994) are closely related to the environmental protection legislation. Permits and other procedures demanded based on these acts include, for example the exploration permit, the mining permit, the environmental permit, the water permit, and the environmental impact assessment procedure. In addition, many other permits related to other laws are required. (Rissanen & Peronius 2013) Permit processes have an important role in pre-surveillance of mining. During each process, prerequisites for permit approval are evaluated, and permit warrants required to prevent environmentally harmful effects of mining are set (Ministry of the Environment 2014).

The permit assessment process begins when the operator delivers the permit application to the permit-granting authority. The main Finnish authorities responsible for granting permits include the Finnish Safety and Chemicals Agency (Tukes), the Centre for Economic Development, Transport and the Environment (ELY Centres), the Regional State Administrative Agencies (AVI), the Municipalities, and the

Council of State. Consideration of the matters of law is performed during the permit assessment process, and the assessment of the admissibility of the operations is made *ex officio*, regardless of any claims that may be represented. If the imposed prerequisites for permit approval are fulfilled, the permit is granted. Conversely, if the imposed prerequisites for permit approval are not fulfilled even after permit warrants are set, the permit cannot be granted. (Ministry of the Environment 2014)

Mining operations can begin after the mining permit, the environmental permit, the planning permission, and the general mine plan are granted by the relevant authorities. It takes usually 2–3 years to go through the different permit processes needed. In addition, planning processes take some time. (Rissanen & Peronius 2013) Thorough project planning plays a central role in a successful permit process and smooth proceeding of the process. If a permit application contains deficiencies, the operator must complement the information missing and this may delay the process, whereas the permit process can be precipitated by thorough planning and verifying the prerequisites of permit admission (Kokko *et al.* 2013).

The current legislation seems to provide a good framework for the fulfilment of high-quality permit processes, and it also enables taking into account both environmental and nature values during the mine planning and in the operational phase. There are, however, certain matters that should be clarified. For example, the relation between different rules and their application areas as well as questions arising from the competences of different authorities are still somewhat unclear. For example, the mutual priority of mining permits, water permits, and environmental permits is not clearly defined in practice (Kauppi 2013).

The key permit processes and the legislation behind them are briefly described in the next sections.

6.1.1 Permits and procedures required by the Mining Act

The Mining Act (621/2011) forms the centre of mining legislation in Finland. Also a number of decrees have been issued based on the Mining Act, the Mining Decree (391/2012) being the most relevant one. The act regulates exploration and exploitation of deposits containing ore minerals. In addition, a cessation of these operations as well as procedures for establishment of a mining area are laid down in the act. The Mining Act aims to secure the prerequisites of ore prospecting and mining activities in a socially, economically, and ecologically sustainable manner. It is especially important to secure public and private interests to fulfil the purpose of the act. In addition, the act aims to promote mine safety and prevent harmful effects and damages caused by the mining activities as well as ensure liabilities for damages. Thus, the act is also in connection with water management procedures in a mine site.

According to the Mining Act, the regulations of 11 other acts need to be taken into consideration when decisions on permit issues or other matters and other activities are made. These acts are:

- Nature Conservation Act (1096/1996)
- Environmental Protection Act (527/2014)
- Act on the Protection of Wilderness Reserves (62/1991)
- Land Use and Building Act (132/1999)
- Water Act (587/2011)
- Reindeer Husbandry Act (848/1990)
- Radiation Act (592/1991)
- Nuclear Energy Act (990/1987)
- Antiquities Act (295/1963)
- Off-Road Traffic Act (1710/1995), and
- Dam Safety Act (494/2009).

All the older acts, such as the Nature Conservation Act, contain also several amendments. The following licences may be granted under the Mining Act:

- **Reservation notification:** An applicant may reserve an area of interest for the purpose of preparing an application for exploration permit by submitting the notification to the mining authority.
- **Exploration permit:** Is necessary in certain circumstances, for example, if the exploration activities pose any risk to people's health or general safety, if exploration cannot be carried out as prospecting work, or if the land owner has not given his consent to exploration. However, the exploration permit is always required when exploration has wide-ranging effects, or in the case of uranium or thorium exploration.
- **Mining permit:** Gives the authority to exploit mineral reserves and carry out mining activities. The mining permit can be granted only after the Environmental Impact Assessment procedure is finished and the mine site has been marked as a mining area in every phase of land use planning (The Finnish Association for Nature Conservation 2013).
- **Mining safety permit:** Is needed for a mine construction as well as for its productive operations. This permit is especially focused on matters related to structural and technical safety of the mine and in prevention of dangerous situations and accidents. The mining safety permit contains, for example, a general mine plan which can further include, for example, the following plans and descriptions: a construction plan of the mine, a plan concerning the buildings and functions to be placed on the site, a geological as well as a rock-engineering description of the ore deposit, mining methods used and filling materials of quarries, a rock-hoisting system, a dewatering plan, landscaping and after-care plans, and plans and surveys made according to the Dam Safety Act, *etc.*
- **Redemption permit for a mining area:** The Council of State can grant the utilization right to an area in the possession of another party. This may be applied if the project is based on public need.

Tukes is responsible for granting mining permits. However, mining permits concerning the utilization of uranium and thorium as well as the redemption permit for the mining area are handled by the Council of State.

6.1.2 Permits and procedures under environmental legislation

Environmental protection legislation is also closely applied to mining. The environmental protection legislation together with the water legislation form the most important regulatory basis for water conservation and water use in the mining industry (Kainua 2010).

6.1.2.1 Environmental Impact Assessment

Environmental Impact Assessment (EIA) is a procedure aimed at promoting identification, evaluation, and consideration of environmental impacts in planning and decision making of projects, increasing the amount of information available to citizens and their opportunities to participate, and observing the means of diminishing harmful impacts. The Act on Environmental Impact Assessment Procedure (468/1994) and Degree (713/2006) regulate EIA procedures. (Kauppi 2013)

The party responsible for the project (*i.e.* a mining company) takes care of performing the EIA procedure. The procedure is required if the total quantity of extracted material exceeds 550,000 tonnes annually or if the area of the open mine pit is larger than 25 hectares. There are also certain individual cases when the EIA is required, *e.g.* if the project is expected to cause similar environmental effects comparable to those where the EIA is required. In addition, if the scale of the project increases above the aforementioned limits, the EIA procedure needs to be followed. (Kauppila *et al.* 2011)

The EIA is not an actual decision-making procedure, but rather aims at generating versatile information as a basis for decision making. Opportunities for the parties to be heard and requests for opinions are also involved in the procedure. The procedure should cover the whole life cycle of the mine from construction to closure and after-care. The EIA consists of two different phases – the assessment program and the assessment report. Comprehensive research on the emissions and operational impacts and on the state of the surrounding environment for environmental permit application can be performed as a part of the EIA procedure. For instance, an assessment of the quality and treatment need of water emissions, Natura Assessment (if required), and baseline studies can be performed. A focal part of the EIA procedure is the assessment of different alternatives for the implementation of the project. The aim of the assessment is to determine the most reasonable overall solution. (Kauppila *et al.* 2011) One of the alternatives is that the project is not carried out at all (Jantunen & Kauppila 2015).

According to the Act on Environmental Impact Assessment Procedure, the EIA should be performed before any actions that may cause harmful effects to the environment are taken. Typically the procedure starts in the very early phase of

the project, and obtaining the overall picture of the project may thus be difficult (Aaltonen *et al.* 2012). The right timing of the assessment procedure is one of the main challenges related to the process. As every project is unique, the suitable placement and starting-time of the EIA procedure should be considered separately during each project. (Ministry of the Environment 2014) Environmental Impact Assessment is finished after the coordination authority, *i.e.*, the ELY Centre of the area in which the project is located, issues a statement on the assessment report. It is important to keep in mind that the EIA is just one procedure in the mine life cycle where the impacts are assessed. Typically, surveys and assessments are still continued after the procedure is finished. (Jantunen & Kauppila 2015)

The Ministry of Employment and Economy has recently published a new guidebook concerning the basis of determination and assessment of environmental impacts and the EIA procedure in mining projects. The aim of the guidebook is to support the assessment of environmental impacts in mining. (Jantunen & Kauppila 2015)

6.1.2.2 Environmental permit

The Environmental Protection Act (527/2014) and Degree (713/2014) aim to protect the surrounding environment from degradation. Mining is defined as action that can cause spoilage of the environment, thus requiring an environmental permit. However, preparatory actions, such as exploring drifts during the exploration activities, do not usually require an environmental permit. The environmental permit covers all subjects related to environmental effects, such as discharges to the air and waters, waste and noise questions, disposal of the mine wastes and after-care of the site, and emission prevention operations after closure. Also sufficient securities are deposited to ensure waste management and closure procedures and after-care of the site. If changes that will cause constituent adding of emissions or risks are taken, the environmental permit must be revised.

For each mine, the environmental permit identifies case specifically the demands of what needs to be monitored and gives guidelines for surface water and groundwater management. If there is a need for freshwater intake, this will be included in the permitting. The permits define quality and quantity of the effluents that are allowed to be released into the environment from the site. Specific demands for the water management infrastructure, treatment procedure and operation are instructed in the permits. The operator is responsible to conduct environmental investigations and present correct information and plans of monitoring to authorities for the permitting process.

Environmental permit is granted by the AVI of the area. A permit application must contain the Environmental Impact Assessment report which means that the EIA procedure must be finished before permit admission. Also the waste management plan for mine wastes and the Natura Assessment (if required) are attached to the permit application. The prerequisites for environmental permit approval require that no effects on human health, other significant pollution or risks to the environment, contamination of soil or groundwater, deterioration of natural

conditions or unreasonable disturbance to neighbours must arise as a consequence of the mining operations.

6.1.2.3 Water permit

The Water Act (587/2011) aims at promoting the use of water resources and the aquatic environment in a sustainable manner, preventing and reducing harmful effects, and improving the state of water resources and the aquatic environments. According to the Water Act, mining operations affecting surface waters and groundwaters require a water permit. The construction of mine sites, mining and concentration activities, as well as after-care of the sites require, almost invariably, the use of water, hydraulic engineering, water works systems, dewatering operations, wastewater treatment, relocation of water channels, and taking account groundwater and surface water protection aspects (Aaltonen *et al.* 2012, Kauppila *et al.* 2011). In addition, sometimes a mining project or a part of it may require a water permit already during the pilot extraction phase (Aaltonen *et al.* 2012).

The water permit is granted by AVI. The water permit decision gives the necessary regulations on avoiding any harmful effects arising from the project and its implementation, landscaping and other remediation, and measures and devices needed to conserve the state of the surface waters and groundwaters. If the project causes environmental contamination in the water area or poses a threat to this, also regulations under the Environmental Protection Act are applied when issuing the permit regulations. If water operations are in close contact to mining operations, applications for a water permit and environmental permit should be made simultaneously.

6.1.2.4 Dam safety

The aim of the Dam Safety Act (494/2009) and Degree (319/2010) is to secure safety in the construction, operation, and maintenance of a dam and reduce the risk of hazard that may be caused by a dam. Dam construction requires a permit process in accordance with the Water Act, the Environmental Protection Act, and the Land Use and Building Act. ELY functions as the dam safety authority.

6.1.3 Other regulatory permits and procedures related to mine water management

As there are also many other acts and statutes relating to environmental protection in mining projects in Finland, it means that apart from those permits and procedures already described many others are required, too. All permits needed in a certain project are listed in their EIA program and the assessment report of a project (The Finnish Association for Nature Conservation 2013).

In addition to the Water Act and the environmental protection legislation, numerous other acts, degrees and lower-level statutes concern water issues and

need to be taken into consideration when planning the mining actions. Some examples of these statutes include (Note: The listing is only illustrative):

- Act on Water Resources Management (1299/2004) and Degree (1040/2006)Waste Act (646/2011) and Degree (179/2012)
- Land Use and Building Act (132/1999) and Degree (895/1999)
- Chemicals Act (599/2013) and Degree (675/1993)
- Act on the Remediation of Certain Environmental Damages (383/2009), Amendment (558/2014)
- Act on the Safe Handling and Storage of Dangerous Chemicals and Explosives (390/2005) and Decree on Explosives (819/2015)
- Act on Compensation for Environmental Damage (737/1994)
- Government Decree on Water Resource Management (1560/2011)
- Government Decree on Waste from the Extractive Industries (190/2013)
- Decree of the Ministry of Social Affairs and Health Relating to the Quality and Monitoring of Water Intended for Human Consumption in Small Units (401/2001) and the Quality and Monitoring of Water Intended for Human Consumption (1352/2015)
- Government Decree on Mining Wastes (190/2013)
- Government Decree on Surveillance of Handling and Storage of Dangerous Chemicals (685/2015)
- Government Decree on Environmental Protection for Quarries, Other Quarrying and Stone Crushing Plants (800/2010)
- Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007)
- Government Decree on the Environmental Protection Requirements for Stations Distributing Liquid Fuels (444/2010)
- Government Decree on the Environmental Protection Requirements for Production Units with a Fuel Power of Less Than 50 MW (750/2013)
- Government Decree on Substances Dangerous and Harmful to the Aquatic Environment (1022/2006), and the amendment (868/2010)
- Government Decree on Urban Waste Water Treatment (888/2006)
- Decision of the Ministry of Trade and Industry on Handling and Storage of Dangerous Chemicals at a Fuel Station (415/1998)

Also a group of other directing methods are related to mining operations. The most important directing methods for water resources protection and water use for

mining include, for example, the Finnish Government decision-in-principle on Water Protection Policy Outlines to 2015, and water management plans (Kainua 2010).

6.1.4 Permit process scheduling

It seems almost impossible to present any chronological generic order for proceeding with the different permit processes and phases required for mining. The ordering may vary depending on each process, and no strict orders for the timing of different permit application processes is regulated. Thus, different permit processes are often overlapping each other and proceed despite their mutual order. (Oksanen 2014, cited in Kokko *et al.* 2013)

Permit processes are usually independent of each other such that obtaining a licence for one permit does not have legally binding effects on the permit process of another permit and the admissibility assessment included in it. The order of the proceedings for different procedures is partially free and partially ordered by regulation. For instance, the applications for a mining permit as well as environmental and water permits can be handled at the same time. (The Finnish Association for Nature Conservation 2013) Figure 17 presents a diagram of the most important administrative permit procedures or comparable procedures associated with mining activities in general and the possible geography of the permit processes for the different life cycle phases of the mining.

The integration of land use plans and local planning, environmental and social impact assessment together with different permitting processes is required when implementing a mining project having significant impacts. The participation of several authorities and other operators is needed when planning and processing the project. For the best results and to improve time management, the various processes will be integrated into the various phases of life cycle phases, in particular those pertaining to data capture and production. This also simplifies understanding the overall picture of the project, especially from a local population's perspective as well as highlights the opportunities to participate. (Kokko *et al.* 2013)

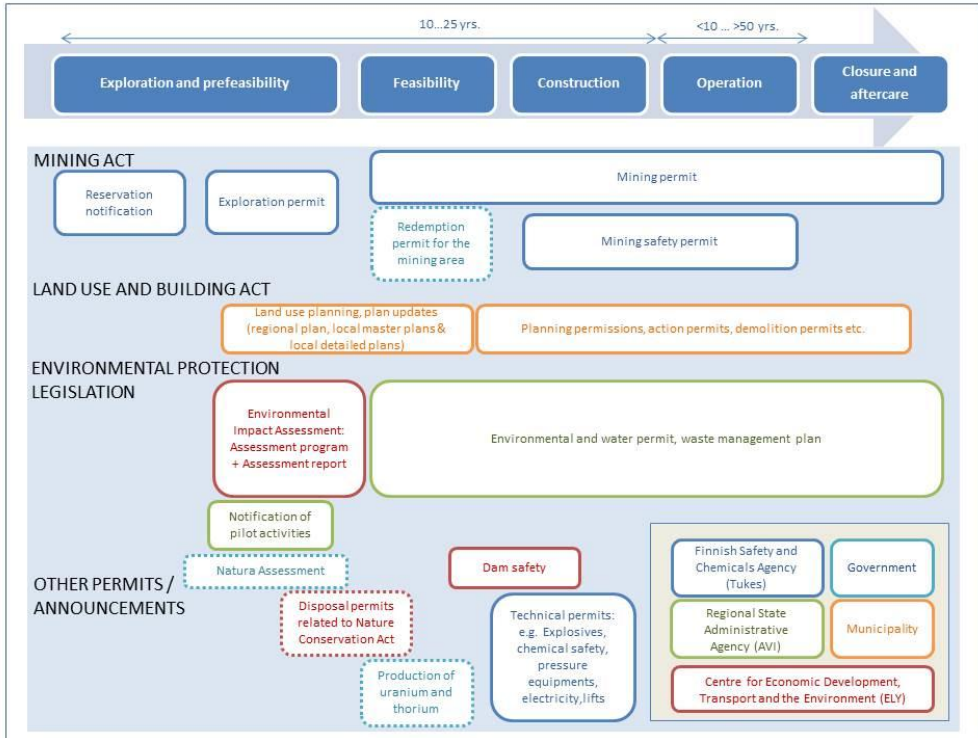


Figure 17. Main permits and other important procedures related to the different phases of mining in Finland.

6.1.5 Responsibilities related to environmental safety

The environmental safety issues of the mining are regulated in many provisions. The main principles of environmental safety are related to the operator's legislative responsibilities as well as pre-surveillance and post-surveillance of the operations. The aim is to prevent harmful environmental effects caused by mining and to supervise the legality of the mining. (Ministry of the Environment 2014)

Regulation of environmental protection and land use planning relating to public law only partially forms the regulative frame that guides the environmental performance of the mining operations. Regulation related to civil law (e.g. neighbourhood relations and compensation for environmental damages) and criminal law (e.g. environmental deterioration) can generate various kinds of responsibilities that should also be considered when planning the mining activities. In addition, self-regulation and good governance of the mining companies which should be based on the principles of corporate governance and environmental protection complete the overall picture. The environmental performance of the mining companies is usually connected to the social responsibility. (Kokko *et al.* 2013)

6.1.5.1 Operator's responsibilities

The responsibilities for operators set in the Environmental Protection Act (2014/527) contain a knowledge requirement, which means that operators must have adequate knowledge of environmental impacts and risks of their activities and of ways to diminish harmful effects. The operator also has a responsibility to prevent the occurrence of harmful environmental impacts or reduce them to a minimum if the impacts cannot be entirely prevented. In addition, emissions into the environment and public sewer need to be minimized by the operator. Operators are also responsible for performing appropriate actions to prevent pollution without delay if the activities cause, or there is an immediate risk for, health hazard or environmental contamination, or to minimize its effects, if pollution has already occurred. In addition, operators must also perceive the principles of caution and care and best environmental practice.

6.1.5.2 Pre-surveillance responsibilities

Pre-surveillance responsibility also concerns mining operators. For example, according to the Environmental Protection Act (2014/527), an operator subjected to licence is obligated to be prepared against the occurrence of accidents and other unexpected situations and limit their harmful impacts on health and the environment. Pre-surveillance includes three different aspects: permit processes, rescue plans, and depositing collaterals for termination of mining activity and ensuring proper waste management. Permit processes are discussed earlier in Section 6.1.

Internal rescue plans are obligatory for certain targets. In addition to internal plans, rescue planning may also contain external plans, both prepared in case of emergencies. The external rescue plan must be compiled if activities may pose a specific danger. The operator is responsible for preparing internal plans, while the rescue department of the area is responsible for external plans. (Ministry of the Environment 2014)

Depositing collaterals is also a part of the pre-surveillance of a mine. The permit authority determines the type and quantity of collateral for each environmental and mining permit in question. The collaterals do not cover environmental hazards or other unexpected expenses, but are meant to secure after-care operations of the mining area in situations where the mining operator is not solvent or otherwise capable of looking after its responsibilities. (Ministry of the Environment 2014)

6.1.5.3 Post-surveillance responsibilities

Post-surveillance of the mine consists of actions of authorities which are involved in the operations that may cause risks for environmental contamination or its harmful effects. Monitoring and supervision regulations for operators and a declaration procedure for exceptional situations have a central role in post-surveillance. (Ministry of the Environment 2014)

The mining operator is principally responsible for implementing the after-care measures after mining has ceased. The operator is also responsible for the operative monitoring of the activity during the operational phase. In addition, the environmental permit consists of requirements for monitoring emissions, effects of the activity, and the state of the environment after mine closure. In proportion, the water permit obligates the operator to monitor environmental effects of the operations on demand. The operator can be instructed to give necessary information for official supervision purposes. The operator must monitor the impacts of its operations and report back to the authorities on the operations, changes made to their operations, and the effects of these changes on the environment. (Ministry of the Environment 2014) When the authorities require the operator to monitor the impact of mine operations on the waters, consideration of what is deemed necessary in the water resources management plan, as referred to in the Act on Water Resources Management (1299/2004), has to be made in order for the operator to organize the monitoring. The data collected during monitoring may be used in compiling a plan for water resources monitoring and implementing monitoring activities in accordance with the act. In certain cases, also joint supervision may be required to supervise the impacts of activities.

According to the Environmental Protection Act, the operator has a responsibility to inform the supervisory authorities without delay in case of exceptional situations, *i.e.*, if any accident, operational failure, structure or equipment demolition or some other similar factor causes discharges or generates waste posing manifest and immediate risk of environmental pollution, or when special waste management measures are needed due to the waste amount or its properties. Based on the notification, the supervisory authority gives a decision containing necessary regulations on restoring the operations to abide by the law and regulations, and removing the harm and danger, and a deadline for performing these actions. On demand, the supervisory authority also gives temporary rules of actions needed to prevent environmental pollution based on the plan made by operator and other information available. The duty of the supervisory authority is to supervise that the operator complies with obligations and decisions on the granting of a licence. Periodic inspections and other surveillance as well as the moderation of information delivered by operators based on permit regulations have a central role in implementing legislative controls that govern the operators. The supervisory authorities have the responsibility to take measures for correcting illegal situations. (Ministry of the Environment 2014)

6.2 EU regulations behind the national legislation

Issues related to mining and mining wastes are also addressed in the EU level legislation. Regulations from the EU especially concern environmental aspects, health and safety, and human rights. (Szczepanski 2012, Scannell 2012) The Member States of the EU are responsible for effectively and properly executing the laws the EU has enacted (Scannell 2012). Thus, although the national legisla-

tion between the different countries may vary, there are certain directives and regulations behind the national legislations. From the perspective of mining and mine water issues, at least the following EU directives are important:

- **Directive on environmental liability with regard to the prevention and remedying of environmental damage (Directive for environmental liability, or the ELD directive) (2004/35/EC)** aims to implement the principle of “polluter pays”, meaning that an operator who causes environmental damage (e.g. an direct or indirect damage to the aquatic environment) or creates an imminent threat of such, needs to either remedy the damage themselves, prevent it without delay (if it has not yet occurred), or pay the costs of performing such actions to the public authorities (Szczepanski 2012, Scannell 2012). The operator needs to immediately notify all relevant aspects of the situation at hand to the competent authority, and take all conceivable actions to instantly control, contain, and remove or otherwise manage all relevant causes of damage, so that further environmental damage and other harmful effects will be limited or totally prevented (Scannell 2012).
- **Directive on the assessment of the effects of certain public and private projects on the environment (EIA Directive) (2011/92/EU), and amendment (2014/52/EU).** The EIA procedure concerns almost all mines, as it is mandatory for open pits and quarries with a surface area over 25 hectares. The type and characteristics of the project’s potentially significant impacts on the environment must be identified. Also the identification of risks of accidents, and a proposal for how to prevent and mitigate environmental damage and risks to health and safety are part of the EIA. A strategic environmental assessment is required for plans or programs prepared by authorities concerning mineral extraction. (Szczepanski 2012)
- **Directive on the assessment of the effects of certain plans and programs on the environment (Directive on strategic environmental assessment) (2001/42/EC)** is mandatory to mining plans. It urges a more integrated approach to territorial planning where environmental aspects are perceived already at an early point in the mine planning. When the EIA procedure of certain project focuses on the assessment of different alternatives on a site-specific or operational level, strategic environmental assessment has more of a macro level effect. In the case of mining, the result of the strategic assessment may be, for example, recognition of suitability or unsuitability of different areas for mining, e.g. mining activities may be encouraged, restricted, or completely discouraged or disallowed in the areas studied. (Scannell 2012)
- **Directive establishing a framework for Community action in the field of water policy (Water framework directive) (2000/60/EC)** focuses on the ecology aspects of river-basin management (Szczepanski 2012). Especially the following obligations of the directive are important to mining; it is required that a good ecological and chemical status of all EU surface waters and

groundwaters must be achieved by 2021, and to be able achieve this goal river-basin management plans have to be compiled. Even the quantitative status of groundwaters is discussed in the directive. (Scannell 2012) In addition, groundwater quality criteria and actions to restrain and restrict the discharge of pollutants in to the groundwater are presented in the **Directive on the protection of groundwater against pollution and deterioration (Groundwater Directive) (2006/118/EC)** (Szczepanski 2012).

- **Directive on the management of waste from extractive industries (Mining waste directive) (2006/21/EC)** is focused on the safe management of mining wastes. Mandatory permits and requirements for building or modifying mining waste facilities are presented in the directive. Financial guarantees, a policy for prevention of major accidents, and development of emergency plans and safety management systems are required from the operator if there is a potential risk either to the environment or public health. (Szczepanski 2012)
- **Directive on the control of major-accident hazards involving dangerous substances (2012/18/EU) amending and subsequently repealing Council Directive (Seveso III Directive) 96/82/EC** is the most important directive dealing with the risk of mining accidents (Scannell 2012). Operative tailings disposal facilities and their ponds and dams containing dangerous substances belong to the scope of the directive. According to the directive, the operators are responsible for, for example:
 - Taking all necessary actions to prevent the occurrence of major accidents, to restrict the consequences of these accidents for health and the environment if they have already occurred, and to perform remedial actions;
 - Notifying the competent authority so that the authority is able to identify the facility in question, the dangerous substances present and the conceivable dangers;
 - Developing a major-accident prevention policy aimed at minimizing the effects of major-accident hazards on health and the environment
 - Preparing an internal emergency plan and a safety report (whereas the competent authority has the responsibility to draw up an external emergency plan), and
 - Notifying the competent authority after a major accident and providing necessary information on the accident and actions to be taken.
- **Directive on the conservation of wild birds (Birds directive) (2009/147/EC)** and **Council Directive on the conservation of natural habitats and of wild fauna and flora (Habitats directive) (92/43/EEC)** form the basis of nature conservation policy in the EU. The Natura 2000 network aims to protect the species and habitats listed under these directives. (Szczepanski

2012) The habitats directive imposes notable obligations on those operators who seek permits for a mining or mining waste project likely to have impacts on protected habitats, fauna and flora.

- **Directive on industrial emissions (integrated pollution prevention and control) (IPPC directive) (2010/75/EC).** Many mining activities are subjected to the IPPC directive due to their notable waste management activities or because some EU Member States have extended their own domestic IPPC regulation to concern mining activities. Even if these conditions are not fulfilled, there are often similar controls required under other less sophisticated authorization systems to make sure that environmental obligations set by the EU are met. According to the IPPC directive, an operator seeking an operating permit must use best available techniques (BAT) to carry out mining operations and all activities directly associated with them. (Scannell 2012) According to the directive, at least the following actions should be included in the permit:
 - Emission limit values for polluting substances that are potentially emitted in significant quantities;
 - Provisions for estimating compliance with these values or a reference to other applicable requirements;
 - Requirements that ensure soil and groundwater protection, as well as waste management and monitoring actions;
 - Requirements for monitoring of emissions;
 - Obligation to inform the competent authority, e.g. the results of emission monitoring at least once in a year;
 - Requirements to perform regular maintenance and surveillance of activities used to prevent soil and groundwater emissions as well as periodic monitoring of hazardous substances from the soil and groundwaters;
 - Actions taken in conditions differing from the normal operating conditions (leaks, malfunctions, operational start-ups, shut-downs, stoppages and definitive cessations *etc.*), and
 - Regulations concerning the minimization of transboundary or long-distance pollution.
- **Regulation concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) (Regulatory framework for the management of chemicals (REACH)) (1907/2006/EC)** covers the use of chemicals in mining activities, whereas mineral ores and ore concentrates are included in the **Regulation on classification, labelling and packaging of substances and mixtures (CLP regulation) (1272/2008/EC)**, which obliges assessment of the risk of physical, health and environmental hazards (Szczepanski 2012).

In addition, mining is one of the activities included in the list of potential soil-polluters in the **Soil framework directive** currently under the proposal phase. According to the proposal, the concentrations of dangerous substances on a mine site need to be monitored, and if sufficiently high concentrations are found, the remediation made according to the "polluter pays" principle. (Szczepanski 2012)

6.3 Communication and community relations

Mining has to be also socially sustainable and acceptable. Local communities, society, municipalities as well as other industries located in the area all have their own differing expectations for the mining operations. (Kokko *et al.* 2013) For instance, local communities usually have generally positive attitudes towards mining. However, communities are unanimous that certain terms have to be set for the mining operations to make them acceptable. These terms pertain to both mining companies and municipalities. The terms targeted at mining companies are especially related to employment aspects, while the terms targeted at municipalities concern communication. Municipal authorities are expected to inform the community of any known impacts of the mine as soon as possible. (Kunnari, cited in Kokko *et al.* 2013)

The right of locals to participate and express opinions has been included in several laws, such as the Mining Act, Environmental Protection Act, Water Act, and Land Use and Building Act (Kauppi 2013). To be able to achieve the local acceptability for the mining project, a genuine hearing of different authorities and the public is extremely vital. Permit processes usually contain a hearing procedure where the parties involved as well as the public are entitled to express their opinions. Hearing procedures for mining projects are arranged during the different phases of the planning and implementation processes. For example, the Mining Act requires that, before the exploration permit, mining permit, gold panning permit, or redemption permit for a mining area can be granted, the approving authority has to give the parties involved an opportunity to submit complaints or state their opinions on the permit application in hand. Also others (than the parties involved) are entitled to express their opinions. The approving authority also asks for comments on mining permit application from the municipality and the ELY Centre of the area. In addition, the authority must obtain other necessary comments and reports for the consideration of a permit. The new Mining Act regulates the procedure to be applied in the Sami Homeland, Skolt area, and special reindeer herding area. (*E.g.* Kokko *et al.* 2013)

A sufficient time limit for giving remarks and opinions is set depending on the nature of the matter. Hearings should not be arranged, for example, during the typical holiday periods. It is also essential to recognize the role of the person/party to be heard and the purpose of the ongoing proceeding phase of the hearing. For instance, the first hearing in the EIA procedure concerns organization of the assessment (assessment program phase) and the final one the results of the assessment (assessment report phase). (Kokko *et al.* 2013)

The following example from the processing of an environmental permit illustrates the course of the hearing process. The permit process begins after the application is submitted. A pending permit application is made public through an announcement put up on a municipal notice board. The announcement has to be on view for at least 30 days. Notification that the announcement has been pinned to the board is made in a local newspaper. Remarks and opinions, as well as statements from municipalities, other authorities and expert institutes are obtained during the phase (not applicable to the Water Act). In addition, the approving authority can obtain other relevant reports from expert institutes. The approving authority will also write a letter of declaration to all parties who are going to be especially degraded by the emissions caused from the mining operations and the impacts of those emissions. These parties may also submit remarks or opinions, and the applicant is asked to respond. The approving authority can organize an overview before permit approval and reserve a hearing for the party responsible for the project before the final decision. The decision is again properly notified. The Vaasa Administrative Court and the Supreme Administrative Court are responsible for handling appeals against the permit decision in Finland. (Kauppila *et al.* 2011, Kokko *et al.* 2013)

Environmental legislation altogether requires an active interaction between the authority, operator, and public. The purpose of hearing procedures is not going to be fulfilled without proper reacting and answering to reminders and opinions. Unilateral acceptance of knowledge without real interaction does not sufficiently promote consolidation of interests or communication between operators. Active interaction should be promoted especially when the aim is to earn a so-called social licence to operate. (Kokko *et al.* 2013)

Active interaction does not mean just giving an opportunity to participate, but also enquiries and other active means of interaction can be used on demand. Local residents and other parties involved can be led to take an active role in project planning, for example, by forming a steering group for the project or interest-specific small groups. To understand a certain part of the participation process or the whole hearing process, questions can be put to the authorities or the persons in charge of the whole project. The role in guiding and communications for the person(s) in charge of the project becomes even more pronounced when the aim is to exceed the minimum legislative requirements for public participation. Also instructions concerning the voluntary hearings must be given to ensure that reminders and opinions are presented in the right phase of the process. (Kokko *et al.* 2013)

In addition to statutory participation and interaction processes, applying for a social licence to operate and maintaining it through self-regulation will also support attaining sustainable development at the local level. Due to the differences from one mining project to another, the obligation to interact cannot be made a mandatory regulation, and thus there is space for self-regulation of the companies. Self-regulation gives an opportunity to perform adaptable participation processes that can take the special characteristics of each project into account. A social licence to operate urges the company to interact with the local community and helps in

implementing environmental performance as well as corporate social responsibilities in mining. In a simplified manner, the social licence to operate means that the local community shows acceptance and supports the mining operations located in the same area. This licence cannot be requested but has to be earned (over and over again). The social licence to operate is mainly related to funding of the project. In practice, it needs to be earned to fulfil the prerequisites of financial markets. The social licence to operate consists of at least these three different levels: 1) social justification, 2) credibility, and 3) trust. (Kokko *et al.* 2013)

A crucial element for the mining company's social licence to operate is to be able to earn and keep the trust of locals with respect to the mining companies as well as municipal and state authorities. Both the approval of society and the social licence to operate are mostly based on spontaneity and internal guidance of the company. Thus, achieving and maintaining the social licence to operate requires that the communication and interaction between the company and locals exceeds the minimum requirements of notifying and involvement set, *e.g.*, in the EIA procedure. Involvement does not end after the environmental permits are granted. In addition, company's strategies on social responsibility and communication need to be fulfilled in practice in a way that satisfies the demands of local communities. (Kokko *et al.* 2013)

One of the main problematic issues concerning the mining industry's social acceptance is the non-transparency of the operations. Information on the project should be distributed from the early phases of the project and transparency of the operations should be developed over the whole life cycle of the mine. Problems concerning the transparency of the operations and openness of discussions may only be related to one operator, but can easily have effects on the social acceptance of the whole operational field. (Kokko *et al.* 2013)

Acceptability of the mining project in a local community can be studied using social impact assessment procedures. The social impact assessment should also be tied to the concept of social licence to operate. It may be one of the vital factors in earning acceptance for mining and the social licence to operate. Interaction and anticipation have central roles also in the success of social impact assessment. (Kokko *et al.* 2013) The well-planned and implemented presence of stakeholders promotes the social impact assessment considerably (Kauppila *et al.* 2011). Nowadays, social impact assessment is a one-time process performed as a part of environmental impact assessment procedure. However, social impact assessment could be extended to a process that begins in the planning phase of the mining project and covers the whole life cycle of the mine. (Kokko *et al.* 2013)

In conclusion, the proper communication between the residents of the area affected by the project, other interested parties, and the mining company has a huge effect on locals' attitudes. If the results of the hearings of the local communities are accurately perceived, if the information available to residents is sufficient, if the mining company is openly dealing with its public relations, if collaterals are set and looked after as appointed, if the mining company has a reliable reputation, and if attendance to the social impact assessment has been easy, then the attitudes

towards mining operations usually are either positive, or at least approving. (Kunari, cited in Kokko *et al.* 2013)

6.4 Water management in the different phases of the mine cycle

The different phases of the mine life cycle require different approaches to water management. The first steps are taken when the environmental baseline study is performed before any alterations to the proposed site are made. The aim of this step is to collect background data on the state of the vegetation, fish, and water systems, *etc.* in the area in order to assess the impact of the mine and its operations on the environment. The first monitoring program will also be developed during this step.

As the phases of the mine life cycle proceed, the water management also develops. The revising and updating of the water management program and related permits is a continuously ongoing process. For example, feasibility evaluations will result in more information on water sources, use, and discharges, *etc.* and thus the water management program created in the earlier phases will be revised. The operations can also be in different phases, for example due to the expansion or closure of some activities during the operational phase. Water management actions in the different phases of the mine life cycle and the permits related are gathered in Table 5 at the end of this chapter.

6.4.1 Phase 1: Exploration, and pre-feasibility studies

Studies to determine the natural state, *i.e.* the baseline conditions of a proposed mine site and its surroundings will be carried out before any alterations are made to the area. The environmental baseline studies will cover all sections of the environment, mining area and surroundings that can be foreseen as having an impact from the mining construction and operations. For example, issues concerning the geology, geochemistry, meteorology, climate, air quality, surficial hydrology, hydrogeology, fish and fish habitat of the area are included in the baseline studies. The data on groundwater level and quality, the description of groundwater forming areas, as well as type and condition of surface water resources prior to mining are to be collected. Basic data on surface waters in the area could include, for example, the dimensions of lakes and rivers, water volumes and flow directions, and descriptions of catchment areas. The natural movements between the various water sources are to be established for the development of the water management program. Hydraulic properties within the soil and vadose zones and groundwater aquifers need to be assessed and data gathered during the exploration phase and continuing through the life cycle of the mine. Changes in hydraulic properties will cause the flow of water from one source to another, and these hydraulic connections need to be considered. Biological information such as benthic flora and fauna, investigations of plankton and fish also needs to be collected. Baseline water

chemistry data is important for establishing pre-mine conditions if there is concern for a potential impact of water quality from mining.

Baseline water quality is determined in four different categories. The physical and chemical parameters of groundwater and surface waters are one category. Baseline water quality should further be determined by measuring the level of contaminants in the sediments, tissue residues, and in the aquatic life to where the contaminants migrate. A comprehensive baseline water quality program will therefore also measure the level of contaminants in the aquatic sediments (second category) as the bottom sediments provide a habitat for algae, plants, microorganisms and sediment-feeding invertebrates. The tissue residues of periphyton, macrophytes, benthic invertebrates and fish form the third class of water quality monitoring as contaminants will be accumulated in aquatic organisms. The fourth category to be monitored in the water quality baseline assessment is the final level of the ecosystem, which can be accomplished by sampling benthic macroinvertebrates and periphyton. This category is the most challenging, as developing a conceptual model to correlate these values to the ecosystem requires considerable effort. (British Columbia Ministry of Environment 2012)

To assure the sufficiency of collected data for the basis of reliable planning, meteorological information on the conditions prevailing at the planned mine site should be collected for several years before any alterations to the area are made. At least in Finland, there are public databases of which weather statistics from very long time periods (*i.e.* prior to the exploration and pre-feasibility phases) can be collected and used as basic data in planning. The information needed for the mine water management program include temperature, humidity, rainfall, snowfall, and snowmelt. This data is necessary, as it enables, *e.g.* evaluation of the degree of evaporation from water sources and gaining information on precipitation either as rain or snow. Information on the current situation can be accessed from the local weather stations.

The foundation of the water management program for a mine site is the water balance model with the water monitoring program incorporated into it. The planning of the water systems is carried out during the pre-feasibility phase, such as water sources, use of water at the site, water treatment, water discharge quantities and quality. The mining companies can use the data obtained from baseline studies in planning the operations and processes in such manner that their impact on the environment is minimal. In addition, the baseline studies can be used as a guide in assessing the environmental impacts of the proposed mining activity. Performing the baseline study helps the mining company to identify where potential hazardous conditions may arise. This information can then be used to develop a monitoring program that will detect the impacts on air and water, should they occur. The monitoring program should continue the baseline study by monitoring the quality and quantity of surface water and groundwater, sediment chemistry and its loading, flow rates, and the aquatic life. (British Columbia Ministry of Environment 2012) The baseline data can be also be used for comparison with the monitoring data.

The planning process of mining operations should always include the plans for closure and after-care of the mine. After-care measures are required for exploration area and mining activity areas. In fact, both the Mining Act and the Environmental Protection Act include quite an extensive regulation on after-care and the provision for it. The Mining Act, for example, requires information on mine closure processes for the permit applications. Preparation of a preliminary mine closure plan may begin already during the pre-feasibility phase. During each life cycle phase, closure plans are updated, and the water monitoring program accordingly. The baseline study provides important data also on how the closure and remediation should be carried out (British Columbia Ministry of Environment 2012).

Exploration continues until the end of an operational phase, and is usually the most wide-ranging during the feasibility phase.

6.4.2 Phase 2: Conceptual and feasibility studies

During the conceptual study phase the preliminary mine plant concept is designed. The conceptual design of the plant will set up the different units of the mining operation and will include the first version of the overall water balance model and monitoring program for the different future life cycle phases. During the conceptual studies, the water cycles for both the plant and the wastewater will be drafted. Water sufficiency and deficiency (*i.e.* availability), and its fluctuations during the seasons, *etc.* will be established and provide knowledge of the water requirements for the different parts of the mine site. The necessity for water treatment facilities will also be assessed and included.

After the various water requirements for the proposed mine are identified, the mine water plan can be established. It will encompass the requirements of the mine plant and water treatment facilities (such as dams and tailings ponds), and the quality and quantity of the water sources (groundwater, surface water, rainfall, evapotranspiration, *etc.*), and discharges from the mine plant. In addition, the water treatment plant and different purification processes may be needed. The plans can include the pumping stations and plans for how both clean and contaminated water will be pumped.

The first plans for water systems made during the pre-feasibility phase will be further developed into the first version of the mine water management program. The feasibility evaluation of the proposed mine will further exploit the conceptual study and define the mine site and its infrastructure in more precise detail. As far as the water management program is concerned, all related matters will be more accurately defined, for example, the sources, disposal, quantities, qualities, and treatment demands of the water. The water management program is implemented through the modelling and monitoring. The information of the operational units and the quality and quantity of water flowing to and from each unit is the basis for the modelling and monitoring program. The evaluation of different process design alternatives during the feasibility phase helps in optimizing the overall water balance as well as water reuse or recycling plans (Department of Water Affairs and Forestry 2006a).

The hydrological studies for water management need to be conducted several times a year, because environmental water conditions change seasonally. Because of climate change, there is a need to be prepared for exceptional weather events. This means that heavy rains (once in 100 years) need to be taken into account for calculating minimum water volume needed in the basins. If effluents are released into a river, the maximum discharge should be calculated and compared to minimum, medium and maximum river flow. During winter time, precipitation as snow is estimated and water equivalent of snow should be followed. In spring, a fast melting period of snow is possible. The quantity of water from melting snow needs to be taken into account in calculations of water basin volume. Melting snow might also cause changes in chemical conditions of waters in basins as well as in natural waters. Gathering all information on natural waters and including it in the mine water balance model will show the possible need to store water accumulated during surplus months and to be used during dry months.

For the development of a feasibility-level water balance it may be enough if simple deterministic simulations are performed monthly or yearly, but as the project progresses to the next phases, more complex models are required with the capability to perform stochastic simulations (Janowicz 2011).

6.4.3 Phase 3: Mine-site planning

After the investment decision has been made, the planning process becomes even more detailed. During the mine-site planning, the water management program will be revised and updated as more specific information is obtained of the plant and mine operations and the infrastructure is planned and designed. For example, the flows from the various water units in the plant and mine area are estimated and a total flow of water to and from each point is set up in the water balance model. The water management program will encompass the mine water plan, (dynamic) water balance model, monitoring plan, and water treatment plan, *etc.* Revisions and updating will continue through the whole mine life cycle.

The environmental baseline studies performed before any alterations to the mine site have occurred set the basis for the water-monitoring program. As the pre-feasibility, conceptual design, and the feasibility phases advance, the water management program along with the monitoring program will progress to become a detailed exact description of the water system on the mine site and it will monitor and relate the state of waters on the mine site to the conditions prior to any prospecting or exploration.

The conceptual study of the mine and plant will be the basis for designing the water management program and its linkages to the process control of the mine for the operational phase. Evaluating the feasibility of the mine includes preplanning the water intake, water cycles, water treatment facilities and the other necessary unit operations needed for the mine to operate. This layout and the monitoring and associated data gathering were the basis for the EIA, which has already been filed before this phase. All of this data is already available and has to be put into written

form stating all the requirements needed to make the monitoring, data gathering and storage unambiguous.

The water-monitoring program and water treatment plans will also be revised and updated. Monitoring is a continuous process that will alter and change as information and knowledge of the mine operation, the environmental conditions, and their impact on each other increases. The plans will include, for example, the yearly amount of freshwater intake, the amount and quality of water assumed to be led to the tailings ponds, the amount of water seen as returning to surface water sites through seepage, and water flows in the water treatment facilities.

A lot of the information gathered in the water management program for the planned mine site is necessary for the permits and licenses required before commissioning of the site. The permits require reporting the impact of the operating mine on the environment and the authorities will evaluate whether the mine is operating according to the permit. During the planning phase, use of the dynamic water balance model allows the mining company to perform sensitivity and risk analysis to conclude where the possible savings and risks lie.

6.4.4 Phase 4: Construction and commissioning

The construction, commissioning, and operation phases set demands on the sampling, analyzing and monitoring of the water on the mine site. Preliminary monitoring plans have been made during the mine-planning phase for each of these phases and the monitoring process will evolve and alterations will be made as the life cycle of the mine progresses. The minimum amount of data to be gathered is set by the licences and permits of the mine site, but an environmentally responsible mining company will go further when setting up their monitoring program.

Construction and commissioning of the mine site start changing the topography, water streams, surface water flows and hydraulics of the aquifers and require precise monitoring of the mine-site waters to be able to follow the impact on the environment. The water infrastructure of the mine site including dams, catchments, and water treatment facilities will be constructed according to the plans and permits. The water-monitoring program is implemented and reporting to the authorities is done.

The water management program is revised and updated again. Increased knowledge of the water systems and their changes due to the construction and commissioning of the mine will revise the program. The monitoring data collected will show the impact of the mine on the environment and thus lead to further revisions of the monitoring program.

6.4.5 Phase 5: Operation

The water management program has been implemented during the previous phases and reporting carried out according to the permits. When operations begin, the planned water management program for the operation phase will be implemented. Revisions will be made according to the operational needs of the mine

leading to revisions and updates for the permits. Sampling sites and monitored parameters will be revised as the collected monitored data is assessed. Mines will operate for many decades, and as monitored data is assessed during operational years, further revisions to the program and thus to the permits will follow. This is a continuously ongoing process.

Operation is likely to involve closing of particular units on the mine site as changes are made to mine operations. It is economically wise and cost effective to remediate and rehabilitate the areas immediately to make them available for other operational use. Also spillages and seepages, *etc.* are remediated immediately and not left to the closure phase. Each rehabilitation and remediation will revise the water-monitoring program.

The first preliminary mine closure plans were done during the pre-feasibility phase. The closure plans are revised during the operational phase requiring updates to the water management plans of the closure phase.

6.4.6 Phase 6: Closure and after-care

Water management will continue after the closure of the mine. Revisions to the permits and programs are made to facilitate this phase of the mine life cycle, and the water management plan for closure is implemented. As the rehabilitation and after-care of the site continues, the water management program, its monitoring and reporting continue in compliance with the permits. The mine area has drastically changed due to the mine operations, but the after-care and rehabilitation are to leave the site in such a condition as to ensure that the legacy left behind is that of sustainability for the local people and their generations to come. (Botha & Chetty 2012)

The preparation for the closure and after-care phase water management should mainly be done during the operation phase, when the personnel and equipment are on the mining site and the mine is receiving revenues from the ore. The post-closure water management should be planned gravity-driven to reduce the maintenance costs and prevent problems caused by possible breakage of the equipment, *e.g.* pumps. The water management structures should be designed resilient to physical and chemical erosion to ensure long life span and low maintenance costs. The water treatment should be designed passive, but the active treatment should be kept operational for the first few years of the closure to prevent a high pollution peak caused by the deteriorating water control structures and during the building and validating the effectiveness of the passive treatment. The monitoring should be online, and it should comprise simple physical characteristics which can indicate any change in the water quality, such as the electrical conductivity or the pH. If any in physical characteristics are noticed, an immediate geochemical sampling and analysis should be conducted and possible intervention procedures should be started to prevent ecological, economic and social effects.

Recommendations and tools for mine closure are presented in Mine Closure Wiki (mineclosure.gtk.fi) which is an open Internet resource on technologies and approaches used in mine closure. The Mine Closure wiki provides guidance and tools for planning, executing and monitoring of mine closure.

Table 5. Summary table of water management in the different phases of the mine cycle. The items will intertwine between the different phases significantly. Mine cycle phases will be case-specific.

Mine phase	Contents/Requirements	Results and information for the regulatory units	Legislative requirements
Exploration	<ul style="list-style-type: none"> Gathering information from other regional mining operations Performing environmental baseline study Water availability Sampling of site for mineral analysis without alterations to environment 	<ul style="list-style-type: none"> Baseline studies of environment, vegetation, fish, etc. including meteorological data, hydraulic properties to be performed at least two years before any changes to the environment to help in developing monitoring program Mineral profile data 	<ul style="list-style-type: none"> Reservation notification Notification of sampling related to prospecting work Exploration permit Notification of field work and construction in the exploration area
Pre-feasibility	<ul style="list-style-type: none"> Planning the use of water on a monthly basis to be implemented in the water balance model Planning water treatment using the baseline study data Preliminary mine closure plan 	<ul style="list-style-type: none"> Site-specific water supply implementation to project requirements Preliminary water treatment plan for water user and discharge What-if scenario from model Information for the EIA Mine closure evaluations 	<ul style="list-style-type: none"> Natura assessment
Conceptual study	<ul style="list-style-type: none"> Planning preliminary water monitoring program Water balance model setup Catchment descriptions and management plans 	<ul style="list-style-type: none"> Mine risk class Knowledge of water sufficiency for the mine life cycle Knowledge on project mine water requirements Water treatment discussions Compilation of the regulatory processes 	<ul style="list-style-type: none"> Comply with Nature Protection Act Disposal permits related to Conservation Act
Feasibility study	<ul style="list-style-type: none"> Mine feasibility evaluations and impact assessment from baseline data Daily water management program that includes water quality and quantity monitoring Water sources and demands for mine Discharge quantity and quality as well as costs Development of a feasibility-level water balance 	<ul style="list-style-type: none"> Mine water management program implementing model and monitoring data Mine water plan including water sources, requirements of the mine, water treatment for use and discharge, etc. 	<ul style="list-style-type: none"> Notification of pilot activities Environmental impact assessment Waste management plan Redemption permit for the mining site Dam Safety

Mine-site planning	<ul style="list-style-type: none"> • Basic and detailed engineering for plans and models: mine water plan, water management plan, monitoring plan, water treatment plan, <i>etc.</i> • Water infrastructure engineering • Linking to process control of the mine 	<ul style="list-style-type: none"> • Water use permits • Water infrastructure construction • Water supply and dam safety approvals 	<ul style="list-style-type: none"> • Comply with Land use & building Act • Water permit • Environmental permit • Disposal permit • Mining permit
Construction and commissioning	<ul style="list-style-type: none"> • Water infrastructure in detail • Water monitoring and reporting • Revisions of models and programs • Linking to process control of the mine 	<ul style="list-style-type: none"> • Water infrastructure (treatment plants, <i>etc.</i>) fulfilled according to permits • Reporting of water qualities and quantities according to permits 	<ul style="list-style-type: none"> • Mining safety permit
Operation	<ul style="list-style-type: none"> • Use of data in water and process control • Water quality and quantity data collection/monitoring and assessment for revision purposes • Water balance model revisions according to collected water monitoring data • Revisions according to operational needs • Update of closure plans • Building of closure, post-closure and after-care water management structures 	<ul style="list-style-type: none"> • Reporting and monitoring of water quality and quantity according to the permits • EIA revisions approval 	<ul style="list-style-type: none"> • Permit revisions and updates
Closure and after-care	<ul style="list-style-type: none"> • Water management plans for closure • Implementation of water quality and quantity monitoring during closure phases 	<ul style="list-style-type: none"> • Water monitoring and reporting during closure in compliance with permits • Rehabilitation plan 	<ul style="list-style-type: none"> • Permit revisions and updates

7. Guidelines and recommendations

Responsible mining companies acknowledge the necessity of understanding the possible long-term advantages and disadvantages of mining. Their aim is to ensure that, in the aftermath of mining, the local community will inherit an invaluable renewable water resource and to ensure that the legacy left behind is that of sustainability for the local people and their generations to come (Botha 2012). Detailed modelling to understand the dynamics of variable rainfall or snowfall (Botha 2012) indicates that an integrated water resource management program can create an opportunity to harvest and bank water when it is plentiful and available, and to release the water for use during dry periods, thereby limiting the impact on bulk water use. These integrated programs are being applied in countries like Germany where mines are within densely populated areas, where harvested water is used as raw water as well as for remediation of pit lakes. (Schultz *et al.* 2011, cited in Botha 2012)

A successful mine water management program will effectively consider water conservation and water demand strategies in allocating the water from within the mine site. Minimization of water loss and water usage, care and protection of water resources and the efficient and effective use of water need to be the aims of the water management program while still being economically efficient, protecting the environment, sustaining water supplies and being politically acceptable. Therefore a successful and responsible water management program will identify the use of dirty, grey, raw and potable water sources by identifying the opportunities to recycle and reuse waters from various sources within the mine site itself.

A successful dynamic water management program will allow sensitivity analysis of the water balance system. The sensitivity analysis will relate various what-if scenarios in order to foresee and predict the bottlenecks and risks related to mining operations. This will give the mining company valuable information on which sections or equipment play a valuable role in the mine process and the water management system and thus allow the mining company to prepare for possible problems or hazardous situations.

Increased efficiency, new technological innovations, sharing of good practices (ICMM 2012), not to mention enhanced education, are all potential factors that help improve the performance in water management. Mining companies must also continue efficient co-operation with other parties on sustainable water manage-

ment and understanding the value of waters. In addition, there is always a connection between natural waters and process waters, and water management processes need to encompass both these aspects. In addition, other water users and the environment in proximity of the mining area should be carefully taken into account. (ICMM 2012) For example, improved seasonal climate forecasts and water sharing and trading among multiple mine sites especially in dry areas are tools that can be used (CSIRO 2013). Sound technical design (hydrogeology, hydrology, metallurgy, and hydraulics, *etc.*) together with proper operation conditions and modification procedures are the main factors behind an effective water management system on the mine site Shelp *et al.* 2009).

Proper water balance management is critical to the mine

- ✓ Benefits of efficient water management and early planning
 - ✓ Reduction of risks and environmental impacts
 - ✓ Cost savings, e.g. optimal storage capacity and diversion of different waters, optimal recycling
 - ✓ Social acceptance
- ✓ Preparation for extreme situations and changes of water balance during mine lifetime
 - ✓ Assessment of water balances in mine-planning phase
 - ✓ Forecasting of hydrological conditions
 - ✓ Sufficient monitoring of hydrological conditions, adaptation to potentially risky situations
 - ✓ Sufficient knowledge about the quality of water
 - ✓ Availability of data from longer periods
 - ✓ Dynamic development of monitoring program, water balance modelling and water management
 - ✓ Warning system linked to the dynamic online monitoring for fast response to arising unexpected situations

7.1 General guides for setting up water management program in Finland

A mine's water management program can be considered to include the following components: wastewater from the concentration plant and the route it takes through the mine site to its final destination including all treatment facilities on the site, discharging of mine-site waters at various points from the mine area into the surroundings, environmental waters flowing into and out of the site as rain, snow, rivers, including also the groundwaters, and monitoring the quality and quantity of the waters in the mine-site area. A comprehensive water management program covers all of this from exploration through to the closure of the mine.

Water management on the mine site is often strictly connected to waste management, as the typical way to store both tailings and used waters is to lead them into the tailings ponds located on the site. The decision to use tailings ponds as

the waste management method automatically means that there will be a huge amount of waters stored in the mine area, and thus the waste management method chosen has a significant influence on water management and the quality of the wastewaters, as well as the formation and changing of the water quality in the ponds. The selection of more active waste management strategies (e.g. paste thickening or filtration methods), however, enables effective water circulation and diminishes the need of water storage on the site as well as environmental risks connected with the tailings ponds. Every mine site is unique and the causes behind the chosen waste management strategy vary, but, for example, in Chile the lack of water acts as a driver towards the use of active waste management strategies to save water for the mining processes. (Nevatalo 2015)

The general steps and guides for setting up a water management program for a mine in Finland have been gathered in this section as a summary of the previous sections. The suggestions are not all inclusive, but should give general instructions on what should be done in the different phases of the mine's life cycle, choices to be made, where additional information is available, and which institutes provide the data required, etc. This section is intended as a short guide to the most important aspects to be considered in relation to the water management of a mine in the different phases of its life cycle (Table 6).

There are numerous guides, tools, Internet sources and databases developed for the use of mining operations, authorities, consultants and researchers to support environmentally sound mining in Finland. For instance, in the beginning of 2015, The Ministry of Employment and Economy published the New Guide for Environmental Impact Assessment Procedure for Mining Projects in Finland. Later that same year Mine Closure Wiki, an open Internet resource on technologies and approaches used in mine closure was launched (www.mineclosure.gtk.fi). In addition to these two, other useful guides and tools for better environmental management of mining are, e.g.:

- Best Environmental Practices in Metal Ore Mining (Kauppila *et al.* 2011)
- Groundwater Studies Check List (Finnish Environment Institute 2014)
- Improving Environmental Risk Assessment for Metal Mines: Final Report of the MINERA project (Kauppila *et al.* 2013), and
- Summary: Good Practices in Assessment of the Environmental Impacts of Mining Projects (Kauppila 2015).

7.1.1 Steps to be taken in early phases

As the first ideas on the mine-site planning begin to take shape, the first skeleton of the water management program should start to take form. Water availability in the area is imaged against the water needed by the mine operation. As the planning continues and operational information is more precise, the monthly water supply becomes more accurate. Decisions have to be made on waste management leading to preliminary plans for water treatment and recycling. In these early

phases, it is quite common that the data on water sources and needs are gathered into a table or spreadsheet for a quick survey. As the planning of the mine site and its water management becomes more elaborate and precise, the decision is made whether the water management program is a proprietary solution that the mining company sets up with its own personnel or is commercial software to be employed. Consultants, research institutes and experts from outside of the company can also be employed to facilitate the planning and execution of the water management program along with its monitoring program. Most of the water management studies should be done in the early phase. This reduces the risk caused by water during construction and the necessary measures for, e.g. water treatment can be designed to comply with the requirements of water quantity and quality.

7.1.1.1 Software programs

A water management platform for mine-site waters must contain the modules necessary to build up the water flow system for the mine site. It has to contain the building blocks for water flow, storage, and treatment, etc. Especially in Finland where there is a surplus of water, it is essential that the environmental water data from the meteorological institute can be implemented, i.e., the seasonal changes in climate, rainfall, snowfall

Good practices

- ✓ Pro-active approach aiming to solving out the causes behind problems beforehand instead of addressing symptoms
- ✓ Water balance management is started during the early planning phases and continues throughout the life cycle of the mine
 - ✓ Needs to be developed and updated along different phases and within phases
 - ✓ Development of knowledge, changes of water balance and operations
- ✓ Applied case specifically, e.g. different phases may be parallel

and evaporation. Because the water management program and permits require water monitoring, a software program that includes modules for inputting the information on the quality and quantity of waters at different points on the site would be very advantageous, instead of a separate software program for monitoring. The platform should also have the ability to produce trend analyses for the most important monitored parameters, e.g. the change in reservoir water content for the future years. It would be very profitable to decide as early as possible on a software program that fulfils the requirements and expectations of the mining company and can be expanded as the project progresses. Each mine is its own case, and the decision of which software program is appropriate is made by the owners. Setting up proprietary software is quite challenging, but may be sufficient.

GoldSim is by far the most popular commercial simulation software solution chosen not only by mines worldwide, but also in many other sectors of business such as nuclear power plants, and municipal water management, etc. One of the

main reasons for its extensive use is its versatility and the ability to expand the program as the needs of the mine require. Different alternatives for planning the mine can be compared during the initial phases which help in decision making. As the mine project progresses, one of GoldSim's strongest assets is risk analysis in the different phases during both the planning and execution of mine operations. GoldSim has further options that can be included, e.g. monitoring of the site analysis parameters in the same software program.

In Finland, a good solution to calculate water balance for planning or operative purposes is to use the WSFS operational simulation system which covers every sub-basin over the whole of Finland. The system automatically gets the latest observations of temperature, precipitation, water level, discharge and other needed data provided by Finnish Meteorological Institute or SYKE as well as other sources. The system uses observations also to follow-up the simulation and forecasting accuracy. A short-term forecast is done using Ensemble Prediction Weather Forecasting data (VarEPS) as an input whereas a long-term forecast additionally uses also climatological weather data. (Juntunen 2015)

With the WSFS system it is possible to focus the simulation on a specific area, like a mine. This way the information of water balance can be provided area-specifically. The local observations from a mine can be used to improve the simulation accuracy. With the WSFS model, the mining operator can better manage water balances in the mining site. Use of weather forecasts enables forecasting water levels and planning discharges and pumping on the mine site. Possible use of the model includes preparation for spring floods by emptying ponds for storage water from snow melt, estimation of the effect of heavy rain fall and calculating the needed outflow from the mine-site reservoir. Thus, overflows and dam breaks can be avoided and consequently prevent leakage of contaminated water. Furthermore, as the model can be rather easily modified to simulate changes of the mining site, it can also be beneficial during a mine-site planning process. The WSFS model has been in operative use at Talvivaara mine after the leakage of a dam to avoid similar accidents.

7.1.1.2 Consultants in Finland

The mining companies may also employ consultants experienced in the field of water management. The requirements for the consultants can be expanded to include not only the water management program, but also the water-monitoring program. There are many consultants available in Finland, both large companies that offer everything from sampling and analysis to building and planning water treatment plants.

Water precipitates as rain and snow, and therefore this form of water source is to be included in the water management program. SYKE and the Finnish Meteorological Institute will provide the mine prospector with information on the local temperatures, humidity, and rainfall, etc. Especially in Finland, where there is a surplus of water during the spring that may even be considered a problem, this has to be incorporated as a water source. If no weather station is within close range of

the planned mine site, the suggestion is to set up a weather station to gather accurate information and thus increase the reliability of the water management tools. The local natural water sources have to be determined along with information on their flow.

The mine operation and the waters discharged should not affect the quality of the environment. The legacy of the mine company is that the environment is left for future generations in as good a state as it was before mine operations. Therefore, baseline study of the environment, its vegetation, fish and waters, should be performed at as early a phase as possible. There are many parties that a mine operator can turn to for this baseline study.

7.1.1.3 Monitoring programs and suppliers

The environmental permit includes the water-monitoring program in which the mine operator specifies the monitored parameters, sampling points, and sampling intervals, *etc.* on the mine site. In Finland there are consultants and suppliers that provide services to facilitate monitoring. Water quantity either water level or flow measurement is measured online. Water quality can also be measured online and currently pH, ionic conductivity, and turbidity are the main online quality parameters that are monitored to show changes. Many of the parameters that are required in the environmental permit monitoring program are performed in the laboratory. Mining companies will have their own laboratories to do routine everyday sampling and analyses, but the supervising authorities frequently require that accredited laboratories be used for analyses and certified persons take samples. The reporting by the mine company to the supervising authority ELY is done once a month. A report is provided on a yearly basis. If something unexpected arises, ELY must be immediately informed of the condition.

7.1.2 Water management after preliminary phases

As the planning of the prospective mine progresses to pre-feasibility and conceptual design, the water management planning has become an important part of the process. The amount of water needed and the wastewater plan have formed the basis for water management, and water treatment plans have to be made. These all play into the feasibility calculations of the mine.

The first water management plans made during the pre-feasibility and conceptual phases should be made as realistically as possible. The site should be broken down into unit cells (or elements) and the accuracy level of this cell conceptualization should be so detailed that it allows the user to simulate scenarios where water management may be modified, causing a change to either flow volumes or water quality or both. Unit cells are to include *e.g.* concentration plant, open-pit, water basins and ponds, dewatering units, waste and waste rock piles, bioleaching piles, and water treatment facilities. The water management plan is to also include the

flow of water to and from natural water sources such as ground waters, surface waters, ditches, brooks and especially remembering rain and snow precipitation.

The basic information needed for the unit cells include size, geological and geophysical information, construction, flow of water between different points. Information on basic chemistry of the water in each cell should be known or estimated, *e.g.*, amount of sulphates and adsorption.

The more realistic and precise this information is, the more reliable the performed what-if scenarios are and these scenarios help in further planning and iterating the water balance platform and management program at the pre-feasibility and conceptual phases. Perhaps one of the shortcomings on the previous Finnish water balance planning has been the correlation of the amount of water content of snow, which is a major issue in the spring during the snowmelt.

As the scenario for water usage and treatment is decided upon, the mine operator is able to decide the monitoring points on the mine site. Supervising authorities require monitoring of the discharge points and all crucial points on the mine site, *e.g.*, dam constructions and tailings ponds, but the mine operator is the expert on his site and will know which points on the site will have the greatest impact on the quality and/or quantity of the discharged water.

The information compiled during the first steps of the water management planning will become a major part of the permits that the mine will submit to the authorities: Natura Assessment, Environmental Impact Assessment, Waste Management Plan, Water Permit and Environmental Permit to mention a few.

7.1.3 Water management during site planning, construction and commissioning

After the decision to build the mine is made, detailed planning of the concentration plant and the water infrastructure will begin. The engineering and construction decisions made will revise and refine the water management program. By now a weather station should have been built on the mine site to give more precise information on rain and snowfall at that particular site. Decisions have been made, *e.g.*, on where asphalt is to be laid (effects on water evaporation from the land, as no water evaporates through asphalt). More precise information on the topography and quality of catchments areas will become available to upgrade the information used in the pre-feasibility/conceptual phase planning. Applications for many of the permits are required in the planning stage: water permit, environmental permit, disposal permit and mining permit. After the permits are granted, water monitoring and monthly reporting to the authorities in compliance with the permits starts. When in the future the situation at the mine changes, *e.g.*, additional water treatment plants or tailings ponds are needed thus leading to changes in the monitoring program, changes to the necessary permits are applied for.

7.1.4 Water management during mining operations

When mining operations commence, the monitoring data gathered is valuable. Analysis will enable using that information for water and process control. The mine will operate for decades, and changes will be made to both the concentration plant and the water processes. The amount of water in the different life cycles of the mine varies and thus a water management platform must be planned for each life cycle phase.

The most important part of the water balance program development is using the information gathered from the monitored data at the various unit cells of the water program. Feeding this information back into the program and updating the mass flows and quality information, results in a water balance platform that is realistic and specific to the mine and its operations. Reiteration is to be continued constantly throughout the whole life cycle of the mine. This is one of the points that software providers are also working on to be in their products.

The basic version of the water balance software programs will only include mixing and transporting phenomena. Reactive chemistry occurring in the water block cells and also between water and the environment can and should be integrated into the software programs to calculate the water chemistry, water-mineral interactions, speciations of water, *etc.* Reactive chemistry software shows the effects on water composition and quality due to aqueous complexation, acid-base and Eh reactions, cation exchange reactions, surface adsorption, precipitation and dissolution, reactions with organic matter and in addition to changes caused by temperature and pressure.

In addition to chemical changes transport of water, heat and solute from variably saturated medias to the area around the cell will further upgrade the model and make a water management platform that is closer to reality. Concentrated media will enhance infiltration, seepage and flow to the surroundings which will include toward ground waters. Knowledge of the stability of the water in tailings, open-pits, waste rock piles, and soil/rock interfaces is important in mapping the transporting of water and solutes.

A comprehensive water management program will allow making what-if scenario testing before the changes are implemented. For example, the concentration plant process will be revised if the raw materials composition changes. Parts of the mine site will also be closed and closure plans made for those sections. The water management program should be continuously developed and revised, and will be subject to revisions as the operational needs and site conditions change and the knowledge about the needs of water management develops further, and accordingly these revisions will be made to the various permits given to the mine for its operations.

7.1.5 Water management after closure

Water management after closure has to be planned and carried out exceptionally well. Final closure of mine operations on the site sets boundaries for water management that differ from the situation where mine operations, personnel and laboratory facilities were available. The amount of water cycling in a closed site differs drastically from the situation during operations. Even during mine opera-

tions there have likely been times when certain areas were closed and valuable information has been gained to help in planning the water management after closure. When the mine operations come to a final stop, the monitoring and reporting duties on the site continue as it is rehabilitated. The fact that the mine's own laboratory is no longer present on the site presents its own challenge. Guidance and tools for planning, executing and monitoring of mine closure can be found in the Mine Closure Wiki (www.mineclosure.gtk.fi).

Table 6. Water management development during different phases of mine life cycle.

PHASE	Minimum information required	Additional information for upgrading	Comments
Pre-feasibility and conceptual	Break up into unit cells (see Figure 18)	Baseline monitoring of water quantity and quality as well as measurement of local weather variables	Model will only be as good as the estimates
	Flow to/from cells, water levels, pumped amounts including <ul style="list-style-type: none"> • pipes • evaporation • snow/rain • waste material input (entrained pore water) <i>etc.</i> 	Seepage Which sets are decided upon to show the quality parameters assessed and their monitoring frequency will be normally the same as those established in the water permit	Risk of forgetting something important
	Information on cells <ul style="list-style-type: none"> • geometries/storage volumes • surface materials • interactions with runoff and groundwater 		
Construction	Site-specific weather station		
	Site constructions that have effect on water management (e.g. asphalt), new ponds, waste rock and rock piles, mine volume increase		
	More reliable topography, surface infiltration and runoff as well as water quality information		
Operation	Inputting monitored, real data	Reactive geochemistry; chemistry from static and kinetic testing	
	Simple mass transport and mixing info	Reaction chemistry	
		Water, heat, solution transport in saturated media	
Closure and after-care	Amount of water circulating	Monitoring of water quality and quantity in discharge points and assess and predict receiving water quality	
	Monitoring		

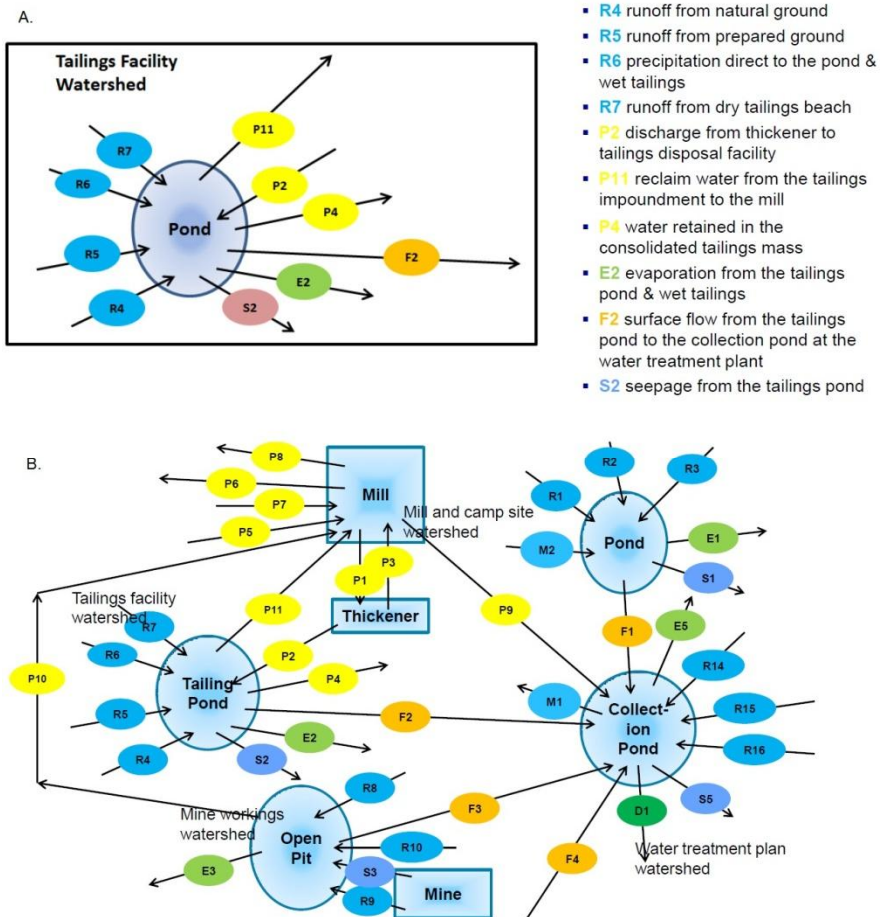


Figure 18. a) An example of a unit cell (a tailings facility watershed), with the flows to and from the shed. b) Water balance summary is the sum of the cells. (Modified from Korkealaakso 2015)

7.2 Recommendations for the future

Stress tests in Finnish mines from Välisalo *et al.* (2014) showed that the mines in Finland are aware of the state of their water management programs and the steps that should be taken (see Appendix and Section 4.1.2).

- At least the older mines should check the hydrological sizing of the dams. Also a dam failure assessment should be made.

- Use of decanting equipment in case of flooding.
- Assessment of adequate basin sizing capacities in case of flash floods.
- Monitoring hydrological conditions for better knowledge of water levels, dam conditions, groundwater quality to improve forecasting hydrological conditions.
- Monitoring weather conditions (snow, rain) and their effects on water levels.
- Installation of process-like water treatment systems that can be adjusted according to different situations.
- Assessing monitoring results to further develop and make adjustments to the monitoring programs (dam monitoring program, water management monitoring program in mine waste areas, environmental monitoring program).

The report by the Ministry of the Environment (2014) also provides strong recommendations on how to improve:

- The communication and cooperation between officials and the mines.
- The safety of mine and mine constructions (dams, foundations).
- The availability of environmental information.

Acting on these points should be the first priority to improve environmental safety and public acceptance of the mines.

To improve public image and approval of the mining sector with a proactive approach to avoid environmental hazards, it is important that all the mines in Finland implement a water management program that gives the operator a full picture of the water balance for the site and includes reliable water monitoring. Many of the current software programs contain the modules and possibility for expansion that fulfil the needs of the Finnish mines, but the programs have not been used to their full potential. With a better understanding of the software program and simulators, the mine operators will become aware of how good a tool the programs are in planning, predicting, and carrying out risk analyses.

Commercial water balance simulators and software programs will develop in the future to improve model correspondence to the state of mine site's water. Linkage and management of the online measurement data being gathered at the mine site to the water balance model for continuous updating and upgrading is of high priority. Another area that the commercial software providers are focusing on is the reactive chemistry occurring at the different, strategic sectors of the mine site.

Strategic sectors are, for example, those that encompass the largest amount of mass and water. What happens in the heaps and tailing areas, be it chemical or physical, has a major impact on the state of the mine site. Software providers are implementing process modelling to *e.g.*, dewatering of tailings ponds. As the programs become more massive, the need to keep the user interface simple and easy remains a priority.

Recommendations for:

Monitoring

- ✓ The monitoring program should progress and develop
 - ✓ Starting from the measurement of baseline water conditions and gathering of meteorological information
 - ✓ Development on the basis of critical assessment of results from longer periods
- ✓ Continuous monitoring of water flow and water level in basins are recommended as good practices
 - ✓ Regular basin inspections are important to confirm the operation of monitoring equipment and water level in basin
- ✓ Regular monitoring of surface and groundwaters and water level combined with weather data are important for forecasting of hydrological conditions, to prevent unexpected water situations
- ✓ Monitoring results should be available in a database with easy access
- ✓ Integration of data from online monitoring tools to water management program enables updating the model

Water balance modelling

- ✓ Development of a good model begins at an early phase in the mine life cycle
- ✓ Conceptual model development is focal
- ✓ Modelling objectives should be clearly defined at the starting point of the modelling and suitable platform for modelling chosen
- ✓ The use of dynamic modelling platform offers advantages
 - ✓ Can be coupled to hydrologic, geochemical, economic, reactive transport and to chemical equilibrium models
 - ✓ Can be connected to on-line monitoring data, when available or monitoring databases
 - ✓ More versatile, suitable for complex modelling tasks and complex scenarios, more detailed evaluation
- ✓ The model should involve the whole mining area and all of its functions over the whole mine life cycle
- ✓ Common and equal formats and methods should be used over the whole area
- ✓ The system should also be flexible to changes
- ✓ Sensitivity and uncertainty analyses should be performed
- ✓ Model should be revised and updated regularly

The reactions and response of the mine area's natural environment to the constructions and wastewaters is a topic that needs to be studied more to be able to take it into account in the water management program. Water seepage and chemical take-up in the terrain and subterranean will have an impact on the future physical properties of the environment. Because the conditions in the water bodies on the mine site, *e.g.*, the ditches, reservoirs and dams may enhance reactions amongst the components, incorporating chemistry into the water management program is gaining importance. Chemical reaction and adsorption modelling of the phenomena occurring in the reservoirs, *etc.* can already be incorporated into the software as an additional user-added module. These phenomena need to be con-

sidered so that the mine operator will have full knowledge of what is happening in the mine-site field areas.

After the mine is closed, the chemistry of the waters and environment will vary from that during operations. During operations, it is likely that small areas have been closed and rehabilitated, and experience of this stage in the mine cycle has increased. Final closure and rehabilitation of the whole mine site will be different in that personnel and laboratories will not be on site, but the obligation to monitor and report to the Finnish supervising authorities continues.

Monitoring of the waters and constructions on the mine site is a field that will definitely take big steps in the near future. Laboratory analyses are the current main analysis method for most quality parameters, but online monitoring will play a big role in the next few years. Digitalization and IoT (Internet of Things) will bring online results to the mine operator and to the supervising authorities. Especially for a closed mine, online monitoring, cloud services, and IoT would benefit the mine companies, which in some cases may locate to another continent. However, regular visits and maintenance of the on-line monitoring systems are probably needed although the systems develop further. And, in the not too far future, “lab-on-a-chip” may simplify water quality analyses.

Speculations are also made as to how the management, software and monitoring will develop in the next decades, and these are presented in Table 7.

Table 7. Estimated development of water balance management.

	Present (<i>state of the art</i>) 2014	Intermediate 2020	VISION 2030
Technology	<ul style="list-style-type: none"> • Software available, only few applications to mines & if applied, only during operation –stage • Monitoring of environmental waters not connected to software (dynamic) 	<ul style="list-style-type: none"> • Dynamic software for environmental waters • Implementation of chemical equilibrium modules 	<ul style="list-style-type: none"> • Dynamic water management including online quantity & quality monitoring and chemical equilibrium/reaction modules • Internet of mine water
Products	<ul style="list-style-type: none"> • Software: GoldSim, Stella, etc. • Online monitoring sensors for flow, level, temp only • Onsite measurements of pH, EC, etc. • Laboratory measurements of ions, BOD, COD, etc. 	<ul style="list-style-type: none"> • Fast lab measurements • Larger array of online sensors 	<ul style="list-style-type: none"> • Water management software for mine specific adaption with user-friendly interface showing water quantity & quality for process, tailings, environment, groundwaters • Online water quality sensors, RFID • Mine water lab on the chip
Drivers	<ul style="list-style-type: none"> • Legislation • Public opinion • Environmental accidents • Water shortage/surplus 	<ul style="list-style-type: none"> • Risk minimisation • Increased water recycling 	<ul style="list-style-type: none"> • Safety for the environment • Public approval
Bottlenecks	<ul style="list-style-type: none"> • Pre-mine operation data not available • Online monitoring, e.g. sensor lifetime • Groundwater management • Information sources required for establishing site-wide water balance is scattered to different stakeholders 	<ul style="list-style-type: none"> • Online measurements for fast reaction to perturbations 	<ul style="list-style-type: none"> • Sensor lifetime • Maintenance costs

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Appendix: Stress tests at Finnish mines

Stress tests at Finnish mines from Välisalo *et al.* (2014): A summary of the mine-specific answers for the questions concerning provision for management of hydrological risk and the means for controlling leakages and dam accidents. Also feedback and notifications from an expert group given on the basis of self-evaluation of the mines are briefly described. (Välisalo *et al.* 2014)

Ihalainen mine (Nordkalk Ltd)

Hydrology (process circulation): 1.5 Mm³ water/a → 0.5 Mm³ to cooling waters. Rest derived to Pikkalanoja via settling treatment. Tailings and process waters are pumped into basin. Seepage waters are collected and pumped back to basins. Closed circulation. Amount of free waters approx. 50,000 m³.

Provision for management of hydrological risks: Daily visiting rounds. Conditions of basins are checked three times per day. Stopping of dewatering pumping. Closing of ditches. Interruption of the process. Extra pumps in ditches. During exceptionally heavy rains process waters can be led to Pikkalanjoki via southern oxidation pond.

Leakage and dam failure management: Dam divided into several segments. Dam dewatering and dam repair.

Assessment and feedback from expert group (concerning water issues):

- Results from monitoring recorded, alarm system in seepage water wells
- Active follow-ups, many systems for emergencies
- If the delay time of the waters discharged out from the basins is sufficient also during exceptional rains, water discharging out from the operational area can be seen as provision
- Risk for environmental pollution is small (according to mine, process waters do not contain harmful substances)
- Provision for power failures: only emergency discharges
- No intention to use pumping in normal situation as provisional mean (which is justified if waters are clean)

Vammala concentrator plant (Dragon Mining Ltd)

Hydrology (process circulation): 1,000,000 m³ of water used annually. Surface waters are pumped to underground mine (used as a storage) via Korvalampi. During high discharges the dam in Korvalampi is opened and water is released to Ekojoki.

Provision for management of hydrological risks: The maximum capacity of the ponds is 100,000–150,000 m³. The area is visually inspected (snow?). The water level of the old mine is monitored. Mine works as buffer storage.

Other: Risk analysis.

Assessment and feedback from expert group (concerning water issues):

- Visual inspections are used to monitor hydrological conditions in the basins. Inspections are made more often during the heavy rains and snowmelt. More systematic monitoring of precipitation and melting would be advisable.
- Groundwaters are not monitored.
- Provision for management of hydrological risk is at a good level. Basin capacity increase is a reasonable good idea to be used in preventing emissions from reaching the water system underneath during possible emergencies.
- The problems with emissions in the concentrator plant are well recognized, good proposals for improvements are made.
- The monitoring program was being updated during the time the enquiry was made.
- Water samples from the environment are taken also for in-house monitoring purposes.
- Provision for power failures: not done, but should be increased.

Jokisivu mine (Dragon Mining Ltd)

Assessment and feedback from expert group (concerning water issues):

- Rather small amounts of water, no dams.
- Chemical quality of waters is analyzed well.
- Provision is adequate (four settling ponds and sufficient pumping capacity).
- Online flow monitoring is used in settling ponds, also online monitoring of N and solids is planned.
- Biggest possible environmental risk connected to storm waters flowing from waste rock areas to the environment, as they are not monitored.
- Provision for power failures: not done, which is ok (waters are not immediately released to environment as they will accumulate to mine pit).

Orivesi mine (Dragon Mining Ltd)

Assessment and feedback from expert group (concerning water issues):

- Only dewatering waters from underground mines are handled, no concentrator plant exists.
- Precipitation and water levels of the basins are visually inspected, continuous monitoring of flows.
- No safety basins, and there is no space for new basins either.
- Real time monitoring of water quality (EC, pH on a daily basis) is a good thing, emissions and detrimental elements are well recognized.
- Mine identifies the need for water treatment plant.
- Risk for emissions after long time power failure exists if the capacity of settling pond is not sufficient.

Kemi mine and concentrator plant (Outokumpu Chrome Ltd)

Hydrology (process circulation): 20,000 m³ of domestic waters are bought. Concentrator plant uses 2.5 Mm³ for process water taken from the settling ponds. Other waters to ponds 1–2 Mm³.

Provision for management of hydrological risks: The area of the tailings ponds is 200 ha. Flood-overflow pipe. Extra storage capacity of waters approx. 1.4 Mm³. Water table lowering by using settling ponds before flooding season.

Leakage and dam failure management: Flow can be directed to another part of the basin. Concentrator plant shutdown.

Other: Risk analysis. Quarry embankment collapse is unlikely. Filter cloth is placed between moraine sealant and in principle minor leakages are blocked by itself.

Assessment and feedback from expert group (concerning water issues):

- Process water quality is good, emissions are monitored from the settling well of the tailings pond and control points underneath the mine. Ability for extra sampling during exceptional situations. These measures seem sufficient as the water quality is good.
- Provision for power failures seems sufficient in proportion to risks.

Kevitsa mine (FQM Kevitsa Mining Ltd)

Hydrology (process circulation): Raw water taken from Kitinen. All waters are led to a water storage pond and surface irrigation field. Closed circulation. Emergency storage capacity in tailings pond is 0.52 Mm³ and in water storage pond 0.05 Mm³.

Provision for management of hydrological risks: The mine has a weather station. Data is gathered for the water balance model. Hydrological modelling performed in 2010–2011.

Leakage and dam failure management: Small leakages controlled by pumping. Repair works and evacuation in large leakages.

Other: Risk analysis. Anticipatory maintenance of pipes and instruments

Assessment and feedback from expert group (concerning water issues):

- Monitoring is extensive and partly real-time, for example, continuous flow measurements and water balance modelling, as well as hydrological modelling are performed, the mine has its own weather station, the capacity of the basins seems very accurately calculated, modelling of emergency situations, monitoring amount of water in snow, provision for detrimental elements.
- Sufficient basin capacity, however, impact assessment and means for risk management in case of exceptional situations (e.g. basin leakages, dam failures) are not adequate.
- Surface water monitoring is comprehensive (daily, weekly, and four times per year), but groundwaters are only monitored four times per year, which is not sufficient.

Nilsjö quartz mine (Sibelco Nordic Ltd)

Hydrology (process circulation): The size of the precipitation area is 34 ha. Rainwaters and runoff waters 292,520 m³. Two tailings ponds, and two seepage water ponds. Water discharges to the environment 148,126 m³.

Provision for management of hydrological risks: Regular, visual inspections. Discharges and lowering of water tables in ponds.

Other: Pumping stations for preventive maintenance and monitoring.

Assessment and feedback from expert group (concerning water issues):

- Monitoring of hydrological conditions is based on visual inspections, which may be satisfactory if water quality and dam resistance do not pose threats to environment.
- Provision for management of hydrological risks is based on additional discharges, which may be acceptable if water quality is good.
- Instructions for exceptional situations and plans for basins elevation exist. The mine has also suggested methods for improvements.
- The provision for power failures seems satisfactory.

Kylylahti mine (Altona Mining Ltd)

Hydrology (process circulation): Dewatering waters collected and treated before settling into Lake Polvijärvi. $Q = 2,300 \text{ m}^3/\text{d}$.

Provision for management of hydrological risks: Collection basins $h=1.5 \text{ m}$. The settlement capacity of basins 9,500 m³.

Sizing: Exceptionally heavy rain once in ten years.

Leakage and dam failure management: By constructing a recycling pumping station.

Other: Risk analysis.

Assessment and feedback from expert group (concerning water issues):

- Discharges and pumping amounts are monitored.
- Monitoring weather statistics might be useful for the improvement of water balance forecasts.
- Weather situations do not have a large effect on the amount of dewatering waters, the amount of basin capacity is noted in action area plan.
- Company sees opportunities to improve the provision for management of hydrological emergencies.
- Monitoring system for treated and discharged waters exist.
- Supervision for perceiving abnormal water quality and preventing environmental loadings exist. The amount of monitoring points is assessed to be sufficient.
- Risk for acidic drainage (to bedrock groundwaters) exists.
- Power failures do not pose significant risk to environment.
- Risks seem to be sufficiently well managed.

Luikonlahti concentrator plant (Altona Mining Ltd)

Hydrology (process circulation): Process water 1.7 m³.

Provision for management of hydrological risks: Water tables are adjusted using settling wells and decantation wells. Spare capacities: tailings pond -, CoNi basin 50,000 m³, settling pond 200,000 m³, Heinälampi 400,000 m³, Suurisuo region 300,000 m³.

Other: Leakage caused by exceptionally heavy rain is unlikely.

Assessment and feedback from expert group (concerning water issues):

- Water levels in the basins, amounts of waters discharged and pumped, and the nearest weather station are monitored.
- Long-term monitoring of weather statistics would improve water balance forecasts.
- Basin capacity in case of exceptional situations is good, also permit for discharges exist.
- Long-time power failure may cause acidic drainage to environment, thus investment for spare engine is necessary.

Laiva mine (Nordic Mines Ltd)

Hydrology (process circulation): Water balance plans for rainy and average years.

Provision for management of hydrological risks: Emergency storage basin capacities 270,000 m³ (water storage basin), 6,200 m³ (HGP1), 500,000 m³ (Vaarainjärvi storage basin). Snow observations, water equivalent, groundwater table. Ditching arrangements, and additional pumping capacity. Water discharges to mine pit.

Leakage and dam failure management: Water direction. Backwaters in leakage areas. Draining in HG 1 basin can be closed.

Other: Risk analysis.

Assessment and feedback from expert group (concerning water issues):

- Meteorological conditions are monitored via online service of Finnish Meteorological Institute. Own weather station would provide locally more exact information.
- The amount of snow, water equivalent and melting are monitored. Groundwater level monitoring is performed.
- Many provisional plans for hydrological risk management exist, however extra discharges cannot be a primary mean for exceptional situations.
- Potential emissions to waters are recognized.
- Plans for provision for power failures exist.

Pahtavaara mine (Lapland Goldminers Ltd)

Hydrology (process circulation): Fresh waters from Soasjoki. The amount of process waters 1.1 Mm³. Tailings pond 3.6 Mm³. Overflow channel to settling pond 0.8 Mm³.

Provision for management of hydrological risks: Meltwaters are blocked using isolation ditches. The extra capacity of settling pond is limited. Tailings ponds are built higher. Water table managed using sluice weirs. Emergency overflow pipes. Extra capacity 0.63 m³ up to 2015. Flood forecasts and water content of snow → estimations.

Leakage and dam failure management: Leakage is collected using exterior ditches and directed to safety basin, from which it is pumped back to waste pond.

Other: Risk analysis.

Assessment and feedback from expert group (concerning water issues):

- Flood periods and exploitation of authoritative information (e.g. moisture content of snow) are perceived in hydrological monitoring.
- Extra capacity of basins, diversions, deduction or stopping of pumping are mentioned as a means for provision of hydrological risks.
- The mine reports to have an extensive monitoring program, however this argument cannot be assessed, as closer information was not given.
- If long power failures exist, it should be taken care that solids do not have access to receiving watercourses as a result of more powerful pumping.

Punasuo-Lahnaslampi (Mondo Minerals B.V. Branch Finland)

Hydrology (process circulation): Internal circulation 5.6 Mm³. Dewatering water 0.705 Mm³.

Provision for management of hydrological risks: Runoff waters directed past the area in a controlled way. Regulation of water table levels. Extra capacity in Lahnaslampi mine. One safety basin. Emergency capacity 60,000 m³ (Talkkiipiiri basin), 120,000 m³ (Soidinsuo basin), 100,000 m³ (Papinlampi basin).

Leakage and dam failure management: Construction of support bench. Restrain of water spreading and diversion.

Other: Pumping of tailings is stopped.

Assessment and feedback from expert group (concerning water issues):

- Capacities of the basins are well known. Meltwaters are managed by using basin capacity.
- Water diversion as a mean for managing extreme hydrological situations; storm waters are not mixed with mine and process waters.
- The mine has monitoring program for water emissions, and its own laboratory for analyses; changes in water quality are noticed relatively fast.
- The mine sees that power failures do not cause any leakages or other emissions, however, reasoning for that viewpoint was not given.

Vuonos (Mondo Minerals B.V. Branch Finland)

Hydrology (process circulation): Raw water from Lake Viinijärvi 0.55 Mm³, mine 0.35 Mm³ and precipitation 0.6 Mm³.

Provision for management of hydrological risks: Minimization of the use of raw waters. Water tables of the basins are kept adequately low by regulating discharges. Emergency storage of the pumping basin 0.45 Mm³. Emergency storage of the middle basin 0.39 Mm³ and emergency storage of the tailings pond 0.2 Mm³.

Leakage and dam failure management: Heading up road systems.

Other: Risk analysis. Tailings slurry pipeline located at inner edge of tailings bank.

Assessment and feedback from expert group (concerning water issues):

- Dam monitoring (more frequently during the melting season), the effects of precipitation are monitored in daily rounds.
- Provision for unusual hydrological situations is based on large basin capacity.
- Also extra discharging can be performed, however possible environmental burden caused from this is not described.
- Excess waters and dewatering waters are pumped to closed mine, the possible drifting to groundwaters is not described.
- Emissions to surface waters and groundwaters are monitored. The company has its own analysis laboratory.
- Large basin capacity is said to prevent environmentally harmful effects in case of power failures.

Pyhäsalmi mine and concentrator plant (Pyhäsalmi Mine Ltd)

Hydrology (process circulation): From mine and concentrator plant 5.135 Mm³. Precipitation 210,000 m³. Rainwaters from courtyards to rainwater outlets, other rainwaters to ditches and further via pumping station to tailings area.

Provision for management of hydrological risks: Own weather station; water table monitoring once a day. Water table measurement data and operating hours from pumping stations. Inspection rounds. Emergency storages 0.25 Mm³ (B basin), 0.084 Mm³ (D basin) and 0.345 Mm³ (C basin).

Leakage and dam failure management: Discharge diverted to another basin. Waters from ditches pumped to basins.

Other: Risk analysis, security plan: persons in charge, actions to prevent accidents, contractors, places of requisition of materials and routing.

Assessment and feedback from expert group (concerning water issues):

- Monitoring of hydrological conditions and basins seems altogether extensive: The mine has its own weather station, continuous surface measuring of surface water pumping stations, and continuous flow direction measures of Lake Pyhäjärvi. The mine has only one discharge point to water system, which simplifies monitoring.
- Groundwater monitoring is also important as wastes are acid producing.
- Extra capacity of the basins seems sufficient.

- Separation of clean surface waters from other wastewaters would ease water management during exceptional situations.
- The mine knows potential environmental risks and has also analyzed the means to manage them.
- Provision for power failures seems sufficient.

Siilinjärvi mine and concentrator plant (Yara Suomi Ltd)

Hydrology (process circulation): Raw water from lake Sulkavajärvi + precipitation + runoff 8.5 Mm³. Waters leaving 5.9 Mm³. Main pit 145 m³/h chemical treatment + fresh runoff waters from settling pond via Sikopuro to Kuuslahti.

Provision for management of hydrological risks: Minimizing the amount of raw waters and maximising circulation. Tailings to Musti basin 5.5 Mm³. New water basin 8 Mm³.

Sizing: Water balance calculations updated in 2012.

Leakage and dam failure management: Prevention / limiting of tailings and water entry.

Other: Risk analysis, security plan.

Assessment and feedback from expert group (concerning water issues):

- Development ideas are presented even if provision for risk is already at a good level, e.g., the investment of a water station to assess the impact of weather phenomena to water balance.
- Other good practices include: automatic sampler in excess water flow of settling pond, flow meter in pumping pipe of pit waters, and samplings once a week.
- Monitoring of fluxes and levels of surface waters, groundwater and seepage waters seems sufficient.
- The capacities of water basins and the possibility to store water in open pit probably give enough guard capacity to manage hydrologically exceptional situations.
- Fresh water diversion is possible due to mine water quality. Pumpings are used to control water levels.
- Emissions from operations are well known.
- Monitoring programs are functioning.
- Provision for power failures seems sufficient.

Sälpä (Sibelco Nordic Ltd)

Hydrology (process circulation): Process waters circulate via circulation water basin. Water intake from sea. Discharges to sea 0.7 Mm³.

Provision for management of hydrological risks: Discharges.

Leakage and dam failure management: Inclinations, shielding of dam borders by using erosion stones.

Other: Risk analysis.

Assessment and feedback from expert group (concerning water issues):

- The answer to provision for management of hydrological risk is rather short, and thus it is hard to assess the type of actions and sufficiency of provisions. The amount of discharges and the operation of pumps are not alone satisfactory means of monitoring hydrological conditions.
- Only a few detrimental elements are identified.
- Pollution monitoring program for exceptional situations is not mentioned.

Pampalo mine (Endomines Ltd)

Hydrology (process circulation): Dewatering waters 0.26 Mm³. Tailings ponds and settling ponds. Secondary settling. 0.5 Mm³ to Riitaoja.

Provision for management of hydrological risks: Discharges and adjustment capacities. Rate of circulation 98 %. Adjustment capacity of settling basins 30,000 m³.

Sizing: Design precipitation 14 days once in 500 yrs.

Leakage and dam failure management: Marking the limits of leakage area.

Other: Risk analysis.

Assessment and feedback from expert group (concerning water issues):

- Mine monitors water levels of the basins and amounts of dewatering waters pumped.
- Monitoring weather statistics would improve water balance forecasts.
- Process water circulation rate is good.
- Amendment for discharging instructions of environmental permit is not a good way to manage exceptional hydrological situations. Also safety capacity should be found.
- Clarification of potential emissions and matters (especially chemicals) that may cause problems is exceptionally rigorous.
- Surface waters, groundwaters and seepage waters are monitored in tailings pond and waste rock area. Seepage waters are analyzed at three-week intervals, which seems to be quite long if the water composition changes.
- The mine sees that continuous monitoring of pH and solids as well as metal analyses would further diminish the possibility of environmental emissions.
- Provision for power failures sufficient.

Suuri-Kuusikko and concentrator plant (Agnico Eagle Finland Ltd)

Hydrology (process circulation): Dewatering waters pumped into settling basin (solids), from which via surface irrigation fields to Seurujoki. Surface waters to irrigation fields. Runoff waters from waste rock dumping area to separate basin, from which pumped to CIL (carbon-in-leach) basin (there has been no need for pumping yet). Process waters are pumped after neutralization to NP3 tailings pond. Domestic waters to Seurujoki after biological treatment.

Provision for management of hydrological risks: Additional capacity 0.5 Mm³ at minimum + 0.4 Mm³ dry margin. Continuous surveillance in basins twice a day.

Groundwater monitoring. Benched bordering ditch. Pumping setup in area between basins. In case of collapsing, waters are diverted to Ruora open pit (not in use).

Leakage and dam failure management: Flow diversion to Ruora open pit. Pumping is stopped and emergency pipeworks are put into operation.

Other: Risk analysis, security plan.

Assessment and feedback from expert group (concerning water issues):

- Weather statistics are monitored, which is good as the mine does not apparently have its own weather station. Comparison between long time weather statistics, water tables of basins and amounts of waters discharged helps in forecasting changes in the future.
- Groundwater monitoring seems extensive, and in general, monitoring of hydrological situations seems comprehensive.
- Runoff waters, dewatering waters and process waters are kept separately.
- Basin capacity designing is performed in the long term, current extra capacity seems sufficient.
- Water management seems possible also during exceptional situations.
- Provision for power failures is sufficient.

Talvivaara (Talvivaara Ltd)

Hydrology (process circulation): Size of the mining area $8.9 + 7.9 \text{ km}^2$. Exterior runoff 11.49 km^2 . Runoff $6\text{-}10 \text{ Mm}^3$. Share of raw waters 2 Mm^3 . Share of stored wastewaters approx. 6 Mm^3 .

Provision for management of hydrological risks: Fresh waters are separated and extracted using dam adjustments and diversion ditches. Process waters circulated inside mining area, storm waters and acidic waters are collected and fresh waters extracted. Safety volume not sufficient because of sudden large-scale gypsum pond leakage.

Leakage and dam failure management: Back pumping and pumping to other basins.

Other: Risk analysis.

Rock waste is used in dam construction and risk of collapsing is very small. Mechanical puncturing of the liner (e.g. movement of pumps) is the probable cause of leakage. Fluid level is kept above inlet pipe and pumps are placed on floats.

Assessment and feedback from expert group (concerning water issues):

- The mine has its own weather station and rain gauges. As water management in the mine has changed drastically lately, it would be important to collect data and make statistical analysis of weather and water table monitoring of the basins to be able to increase predictability in the future.
- It is important to arrange new dams and pumping routes for fresh runoff waters, and to raise safety capacity of the basins.

- Due to the recent problems, the mine probably has good knowledge of its emissions to environment nowadays, and has unusually good capability to assess the difficulties related to the operations/emissions.
- Environmental-/obligatory monitoring program is wide and versatile.
- Waters discharged to nature are analyzed on a weekly basis, thus possible changes are identified soon.
- Additional monitoring in addition to routine monitoring is performed.
- Continuous monitoring of pH and EC from effluent waters.
- Monitoring of groundwater quality was not evident from the answer.
- Provision for power failures is sufficient.

Title	Guidelines for mine water management
Author(s)	Henna Punkkinen, Lea Räsänen, Ulla-Maija Mroueh & Juhani Korkealaakso (VTT); Samrit Luoma, Tiina Kaipainen, Soile Backnäs, Kaisa Turunen, Kimmo Hentinen & Antti Pasanen (GTK); Sari Kauppi, Bertel Vehviläinen & Kirsti Krogerus (SYKE)
Abstract	<p>Mining influences the quality and quantity of water in the mine area and in its surroundings and changes hydrological conditions. Although mining companies have long been conscious of the importance of water management, they still face environmental problems. In fact, water management is at the moment the most challenging stress factor concerning environmental safety in Finnish mines.</p> <p>This report is a part of the WaterSmart project, which aims to improve the knowledge of the actual water quantities and of the water balances in mining areas. Principles of sound water management in different phases of the mine's life cycle are introduced in the report. For example, when establishing a new mine, the planning of water management actions should be started already in early project planning phases. Additionally, the use of a comprehensive and proactive approach that develops throughout the mine's life cycle is important, not to forget legislative requirements or aspects related to social acceptance of mining.</p> <p>This report describes the current status, needs, and challenges of mine water and water balance management especially in Finland and identifies expected future needs for water management solutions. The tools for efficient water management are presented with the main focus on water balance modelling programs and water quantity and quality monitoring practices. It is recommended that mines have a constantly updated water balance management system, which not only takes into account all natural waters on the site and in the surroundings but can also be integrated with the process control systems of the mine. This enables improved forecasting and management of the water volumes. With the help of dynamic modelling, it is possible to predict the effects of operational modifications and sudden changes in water balance, which allows comparison of different mine plan alternatives as well as better provision for risk situations. With dynamic modelling, it is also possible to integrate the monitoring data with process control and thus enable updating the model. It is recommended to have an online monitoring system at least for water level and flow at strategic points on the mine site. A possibility to monitor online also the weather conditions and water quality parameters enables ever more extensive real-time follow-ups.</p>
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Nimeke	Hyviä käytäntöjä kaivostoiminnan vesienhallintaan
Tekijä(t)	Henna Punkkinen, Lea Räsänen, Ulla-Maija Mroueh & Juhani Korkealaakso (VTT); Samrit Luoma, Tiina Kaipainen, Soile Backnäs, Kaisa Turunen, Kimmo Hentinen & Antti Pasanen (GTK); Sari Kauppi, Bertel Vehviläinen & Kirsti Krogerus (SYKE)
Tiivistelmä	<p>Kaivostoiminta vaikuttaa kaivosalueen ja sen ympäristön vesimääriin ja vesien laatuun. Vaikka kaivosten vesienhallinnan merkitys ympäristön suojelussa on tunnettu jo pitkään, on tilanne monilla kaivoksilla yhä kaukana ideaalista ja vesienhallintaan liittyvät haasteet ovat yleisiä. Tänä päivänä vesienhallinnan parantamista pidetäänkin tärkeimpänä suomalaisten kaivosten ympäristöturvallisuuteen liittyvänä kehityskohteena.</p> <p>Tämä raportti on osa WaterSmart-hanketta, jonka tavoitteena on kehittää kaivosten vesiin liittyvää riskinhallintaa parantamalla tiedonhallintaa kaivosalueiden todellisista vesimääristä sekä vesitaseista. Raportti esittelee hyvän vesienhallinnan periaatteita kaivostoiminnan eri vaiheissa: esimerkiksi uutta kaivosta perustettaessa vesienhallinnan suunnittelu ja vesien tilan monitorointi tulisi aloittaa jo kaivoksen suunnitteluvaiheessa. Lisäksi korostetaan ennakoivan, kokonaisvaltaisen ja kaivoksen elinkaaren myötä päivittyvän suunnittelun ja toiminnan tärkeyttä. Myös lainsäädännön mukanaan tuomat vaatimukset ja kaivostoiminnan sosiaaliseen hyväksyttävyyteen liittyvät näkökohdat on huomioitu.</p> <p>Raportissa kuvataan vesien- ja vesitaseen hallinnan tilaa erityisesti suomalaisilla kaivoksilla ja nostetaan esiin vesienhallinnan haasteita ja tarpeita nyt ja tulevaisuudessa. Hyvän vesienhallinnan työkalujen esittely keskittyy vesitaseiden mallinnusohjelmiin sekä vesien määrän ja laadun seurantamenetelmiin. Jatkuvasti päivittyvä luonnon- ja prosessivesien yhteinen vesitaseen hallintajärjestelmä mahdollistaa nopeiden vesitilanteiden muutosten huomioinnin sekä tulevaisuuden ennakkoinnin, ja sen käyttö on suositeltavaa. Dynaamisen mallinnuksen avulla voidaan mm. varautua riskitilanteisiin, arvioida erilaisten suunnitteluvaihtoehtojen vaikutusta sekä luoda systeemi, jonka avulla seuranta- ja prosessiohjausdata voidaan kytkeä malliin ja näin mahdollistaa mallin päivittyminen. Jatkuvat toiminta ja automaattista veden pinnankorkeuden ja virtaaman mittausta suositellaan kaivosalueen tärkeimpiin kohtiin mallin verifiointiseksi. Veden laadun ja sääolojen online-monitorointi mahdollistaa lisäksi entistä kattavamman reaaliaikaisen seurannan.</p>
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This report is a part of the WaterSmart project, which aims to improve the knowledge of the actual water quantities and of the water balances in mining areas. The report describes the guidelines and related good practices for water management in different phases of mining therefore enabling selection of the most appropriate calculation models and measurements as well as control, reporting and decision-making practices.

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