A Review of Key Factors Affecting Mine Dewatering and Slope Depressurization

J. Dowling  Schlumberger Water Services, Tucson, USA
J. Reidel  Schlumberger Water Services, Reno, USA
G. Beale  Schlumberger Water Services, Shrewsbury, United Kingdom

Abstract

Control and management of groundwater is a fundamental component of most successful large open pit mining operations. The key factors that affect groundwater control can vary significantly according to site-specific hydrogeologic conditions, the size of the mining operation, and the mine plan. This paper reviews typical hydrogeological settings for mine operations, criteria for planning, investigating and implementing an integrated dewatering and slope depressurization program.

1 Introduction

The majority of open pit mining operations require some form of groundwater control. This may range from the operation of minor sumps in the lowest working area of the pit floor to the installation and operation of major dewatering well fields that require considerable planning, investment and maintenance.

At one extreme, for some mines excavated below the water table, evaporation of minor groundwater seepage from the pit floor or pit walls in a strong and stable rock mass can take care of all the requirements for groundwater control. At the other extreme, the largest mine dewatering operations tend to be those installed either within regional carbonate aquifers or recent sedimentary basins. For these operations, major pumping operations are necessary using external wells to control groundwater inflow to the pit, and to lower the pore pressure in the rocks making up the pit slopes.

2 Key factors that affect the scale of groundwater control

At any given site, five key factors that dictate the scale of the groundwater control system are as follows:

1) **The regional hydrogeologic system.** The mines that require the largest dewatering rates are generally those located in regionally extensive groundwater basins. Examples of these are the Goldstrike, Lone Tree and Robinson mining operations in Nevada, the Shaimerden project in Kazakhstan, and the Rhur and Bolzhoy basins in Germany and Poland. Mines in areas of exceptionally high rainfall, or those located close to surface water bodies, may also require high volume pumping systems.

2) **The size of the pit, and its depth and rate of excavation below the water table.** An obvious general rule is that mines which go deeper below the pre-mining groundwater table require more consideration of groundwater control. However, because many mine-site settings occur in low-porosity crystalline rock, with low groundwater storage potential, rapid drainage is much easier to achieve if the host rock is not connected to a recharge source or to more porous and permeable groundwater units in the surrounding area. The Escondida pit provides a good example of this. It is much easier to generate and maintain drawdown on the east side of the pit than on the west side.
because the rocks in the east wall receive on-going recharge from saturated alluvial basin deposits located immediately east of the mine.

3) **The prevailing climatic conditions.** The amount of rainfall in the mine area is an important factor controlling the required scale of the groundwater control system. Many tropical mining operations require considerable groundwater control, even those located in rocks of low permeability. Where high rainfall tropical mining operations are located in permeable host rocks, the pumping rates required for dewatering can be very high, such as at Grasberg or Nchanga. The required pumping rates at these operations are many thousands of gallons per minute.

4) **The hydrogeologic characteristics of the rock mass in which the excavation takes place.** While the local-scale hydrogeology is important, it is often subordinate to the regional setting in terms of influence on the required overall pumping rate for groundwater control. However, the local-scale hydrogeology is clearly important for determining what type of dewatering measures are required, and the extent to which the pit slopes become depressurized. This is discussed in detail below.

5) **The geomechanical characteristics of the pit slopes.** The presence of groundwater pressure in open pit slopes can have a fundamental influence on slope design angles and slope performance. For some mines with a strong and stable rock mass, such as an unaltered granite or limestone, the requirement for significant pro-active reduction of pore pressures in the pit slopes may be less than for mines where lower-strength materials occur within the slopes. As such, the goals of the groundwater control system are often more readily achievable in stable rock mass environments. However, in steeper, high strength rock slopes, the potential for sudden brittle failure under small mining induced strains is increased when the pore pressure is elevated. The presence of major geologic structure and impact on slope design and performance can also dictate a requirement for groundwater level reduction, with slope stability the driver.

### 3 Consequences of mining below the water table

The consequences of mining below the water table fall into two general categories, as follows:

Groundwater inflow and the presence of saturated rock lead to a reduced operational efficiency and increased mining costs because of:

- Loss of access to parts of the pit area due to inundation and in some cases, an ultimate loss of the ability to mine.
- Wet and inefficient drill-and-blast process, which typically requires greater use of explosives, or the use of slurry or emulsion, and can cause poor overall blast performance and, in some cases, detonation failure.
- Increased equipment wear, including damage to tires, electrical components or even equipment corrosion, leading to overall higher maintenance requirements.
- A general loss of efficiency that may lead to higher loading costs, increased haulage costs because of the weight of water in the ore or waste rock or, for some ore types, elevated product moisture contents that must be managed prior to shipping and delivery to the customer.

Groundwater has a detrimental effect on slope stability because:

- Groundwater pressure acting within discontinuities and pore spaces in the rock mass reduces the effective stress with a consequent reduction in shear strength.
- Either the slope must be designed with a low factor of safety or requires flattening, leading to additional stripping or other remedial measures to compensate for the reduced overall rock mass strength.
4 General mine dewatering versus slope depressurization

The typical focus of a general mine dewatering system is the first category; to improve operational conditions and reduce mining costs. The focus of a pit slope depressurization program is the second category; to allow improved slope performance (Factor of Safety increase) or increased slope design angles.

Mine dewatering and pit slope depressurization are clearly inter-related and, at many mines, both dewatering for operational efficiency and depressurization for slope performance are required. However, there are two important differences:

1) General mine dewatering programs aim to achieve a general lowering of the groundwater table in the mining area to below the level of the working pit floor, or below some other defined target. Pit slope depressurization programs aim to dissipate groundwater pressures more locally, generally in well defined sectors of the mine. If any given sector of the pit slope is connected to porous and permeable unit(s), it will not generally be possible to achieve the required depressurization without first dewatering those porous and permeable unit(s).

2) General mine dewatering programs often involve high-volume pumping, requiring integration of the system into the overall mine water balance, and potentially off-site discharge. Pit slope depressurization programs usually produce comparatively low volumes of water, meaning that downstream discharge management is often less onerous.

However, the objective of either a general mine dewatering or targeted slope depressurization program is the same: to achieve a lowering of the total head of water to a pre-determined target. For a general mine dewatering program, determination of the targets is often relatively straightforward because they are normally related to the elevation of the pit floor at a given time. However, the required pumping rate to achieve the defined target can vary widely between different operations. For a pit slope depressurization program, determination of the targets is usually more complex because the required pore pressure distribution is inter-related with the geomechanical behaviour of the mine, slope design and performance, risk tolerance, and acceptance criteria for a given mine design and operation.

In some instances, a general mine dewatering system can achieve the required depressurization of the slopes, so there is no requirement to implement focused programs aimed at depressurizing the pit slopes in localized area or specific sectors of the pit. However, for a large number of pits, additional, dedicated measures are required for some or all slope sectors specifically to reduce pore pressures that result from the presence groundwater. This is particularly important when the presence of groundwater pressure is a controlling factor in slope design and performance.

The relationship between general mine dewatering and pit slope depressurization can be divided into five broad groups. The most important factors controlling this inter-relation are the local-scale hydrogeological setting (item #4 above) and the strength of the material that forms the pit slopes (item #5 above).

4.1 Group 1 – Mines excavated below the water table within porous and permeable rocks that are hydraulically interconnected

For this category, the general mine dewatering program can adequately reduce pressure in all pit slopes, requiring no additional localized measures to dissipate pore pressure.

Advanced lowering of the water table using wells causes gravity drainage of the pore spaces within the rock mass being excavated. If the permeability of the rock mass is high, and the rocks are hydraulically connected, the profile of the water table behind the pit slope will be relatively flat, as a result of nearly uniform rock mass drainage.
An example of this category is the Cortez Pipeline Operation in Nevada, where in excess of 23,000 gpm of groundwater is pumped from peripheral and in-pit dewatering wells in a highly-fractured limestone rock mass, where no localized slope drainage measures are required.

### 4.2 Group 2 – Mines excavated below the water table that have lower permeability rock occurring in some sectors

For this category, the rock mass may not drain fully in all sectors as the water table is lowered. The bulk of the rock mass and sectors are readily drained, but effective advanced dewatering is not possible in some sectors, where alteration or variations in lithology creates extremely low permeability.

The permeability may be low in parts of the pit area and/or the slope drainability may be poor due to lack of open fractures or pore spaces. As a result, groundwater will move very slowly and pressure within some parts of the rock mass will not dissipate. As the mine excavation is deepened, pore pressures within all or part of the slope may need to be proactively reduced using targeted, localized depressurization measures.

An example of this category is the northeast and southwest walls of the Sleeper mine in Nevada, where in excess of 20,000 gpm was pumped from alluvium and permeable volcanic tuffs using wells, but the drainage of argillaceous rocks in certain sectors of the pit wall was poor, and required localized control with in-pit horizontal drain programs.

### 4.3 Group 3 – Mines excavated below the water table containing perched groundwater zones

In other situations, perched groundwater zones may develop at higher elevations as the main water table is lowered. These perched zones may occur associated with less permeable structures, bedding or alteration, that impede vertical groundwater movement and result in pore pressures that are ‘de-coupled’ from the dewatered groundwater system. This situation occurs to some degree at most dewatered open pit mines. The extent to which it is important to the mine is normally a function of inter-ramp scale slope design and performance.

An example of this category is the north wall of the Whaleback iron ore pit in the Pilbara, Western Australia. Dewatering of the permeable hematite formations is relatively straightforward using dewatering wells. However, shales and clay-altered materials in the upper slopes do not respond to the hematite pumping and retain elevated pore pressure which may create instability for certain pushbacks.

### 4.4 Group 4 – Mines excavated below the water table where geological structures form barriers to groundwater flow

For this category, the rock mass may not drain because geological structures act as impediments to groundwater flow, creating compartments of trapped water with unchanged (and therefore high) pore pressure. As a result, the general mine dewatering program does not dissipate pressure in all pit slope sectors.

As the excavation is extended and approaches the structural compartments, localized measures become necessary to penetrate the structures and drain the water behind them. Most large open pit mines in hard rock settings encounter structural compartments that influence groundwater heads and movement to some extent. Integrated hydrogeologic and geotechnical interpretation is required to determine whether active dewatering of the compartments is important. Examples of mines with structural compartments that require proactive drainage measures to support pit slope performance include the South Wall of the Chino Mine in New Mexico and Rio Tinto-Minerals Boron Operations in California.
4.5 Group 5 – Mines excavated above the water table where seasonal precipitation leads to perched groundwater in upper stratigraphic intervals.

Control of groundwater pressure may be required to support slope performance, even though the open pit is entirely above the water table. Localized infiltration of precipitation can build up on low-permeability layers and form perched zones of groundwater, leading to locally elevated pore pressures in the pit slopes.

There are many examples of this category in tropical mine settings, where infiltration of local rainfall can lead to permanent or transient pore pressures in the wall rocks. Another example may be where an open pit is excavated through a paleochannel or active stream deposits.

5 Setting up a hydrologic investigation program to support “stage-gate” project development

Most new mining projects or expansions require detailed hydrogeologic characterization, and investigation of dewatering requirements for mine planning and permitting. An integrated approach to assessment of groundwater pressure and its influence on mine geotechnical design and performance is common practice, from the pre-feasibility stage and onward.

The scope of the investigation program to determine groundwater control requirements depends on the stage of the project, the hydrologic setting, and the local regulatory requirements. In addition, the scope may depend on the individual guidelines of the particular mining company in terms of detail and confidence required at each stage of project development.

General guidelines for obtaining hydrologic data for a ‘Greenfield’ mine development project are as follows:

- **Scoping-level project studies:**
  - Pre-existing public domain regional hydrologic data.
  - Regional climatological data.
  - Mine area geologic data from the mineral exploration program.
  - Preliminary surface water measurements and mapping.
  - Hydrogeologic data obtained from “piggy-backing” onto mineral exploration and infill drilling and geophysics programs.
  - Standpipe piezometer construction and monitoring, using mineral exploration drill holes.
  - ‘Order-Of-Magnitude’ scoping study that identifies significant hydrologic conditions that may have significant impact on mine design, operation, permit-ability or economic viability.

- **Pre-feasibility level studies (PFS):**
  - Climatological station established on site.
  - Dedicated drilling and construction of standpipe monitoring wells.
  - Establishment of surface water gauging stations, specifically located in the hydrogeologic catchment of the mine, for baseline groundwater level and chemistry information.
  - Baseline studies for surface and groundwater (typically a 12-month monitoring period, flows, levels, chemistry) in the hydrologic catchment of the mine.
  - Multi-level grouted-in vibrating wire piezometers (VWPs) installed in geotechnical diamond drill holes to provide dedicated monitoring of groundwater heads and gradients near and within the proposed open pit footprint.
Packer testing or other in-situ testing of mineral exploration, infill and geotechnical core holes, to define the local permeability ranges of the major lithology, alteration types and structural domains.

Extended airlift testing of reverse circulation mineral exploration or infill drill holes to characterize local scale fracture hydraulics.

Pumping tests of any pre-existing water wells in the immediate mine area to define the broader-scale groundwater system characteristics.

Construction of a first-generation 3D groundwater model, to test the main elements of the hydrogeologic conceptual model, develop order of magnitude pit inflow estimates, and define key data gaps and uncertainties.

Preparation of a pre-feasibility mine hydrogeology and dewatering study report, including preliminary dewatering engineering design with +/- 35% costs for start-up through the mine break-even period, plus order of magnitude costs through Life of Mine (LoM).

Preparation of a “gap-analysis” to help focus data requirements for the subsequent feasibility study.

- Feasibility level studies (FS).
  - Additional climatological stations and detailed precipitation and evaporation, and design storm event analysis.
  - In-fill studies for surface and groundwater baseline.
  - Installation of test production pumping wells, or drainage trials using horizontal or vertical pilot holes, depending on site conditions. A pilot scale dewatering or drainage program is essential at the feasibility level. For permeable systems, test pumping at least 10% of the expected production dewatering rate is the rule of thumb.
  - Installation of additional multi-level VWPs to infill identified data gaps and to monitor the production pumping and drainage trials.
  - Development of a refined 3D groundwater model using the additional field data and responses to pumping and drainage trials for transient model verification.
  - Development of a detailed prediction of groundwater inflow rates to the mine on annual increments, implementing the proposed annual pit shells into the 3D groundwater model.
  - Development of annual predictions of pit slope pore pressure distribution using the 3D model and 2D sector specific models, with one-way coupling of results into the geotechnical design study models.
  - Design of the proposed mine dewatering program.
  - Integration of the mine dewatering plan into the site-wide water balance.
  - Planning and design of off-site water treatment and discharge system, as required.
  - Hydrologic and engineering design of dewatering system and associated infrastructure; Capex and Opex to +/- 20% for the break even pit, and +/- 30% for the LoM pit.

- Detailed design-phase studies.
  - Pilot hole drilling using reverse circulation equipment for production dewatering well placement.
  - Construction of 30% of the start-up production well requirement, with well placements tied to the start up mine plan.
Long term production pumping trials which should run for at least two weeks and preferably longer.

Installation of specific multi-level VWPs for monitoring of test pumping and slope drainage trials, with emphasis on the starter pit.

Design of pit perimeter surface water diversions and in-pit surface water and drainage pumping system.

Updating of the conceptual groundwater model based on the production dewatering trials.

Confirmation of the dewatering flow rate requirement for the mine project break-even period using the 3D groundwater flow model.

Development of detailed pore pressure models that are integrated with slope design models, with emphasis on the ‘break-even’ pit slopes.

Detailed design; Capex and Opex for the dewatering and slope depressurization plan for the break-even pit.

Detailed design; Capex and Opex of the dewatering discharge management system

Preliminary dewatering and slope depressurization design; Capex and Opex for the LoM pit to +/- 20%.

**Operational requirements**

Definition of dewatering targets, and slope depressurization targets for key slope sectors, tied to the mine plan.

Design of a phased implementation plan for the defined programs.

Progressive construction of dewatering and slope depressurization measures and surface water controls.

Installation of the required monitoring points to allow continuous monitoring of drawdown towards the defined targets.

Interactive monitoring of the individual well and pump efficiency and performance leading to design changes as appropriate.

Interactive monitoring of the dewatering system performance as a whole.

Updating of the groundwater model and dewatering rate predictions.

Implementation of milestones for update and planning of the ongoing dewatering system based on system performance and refined dewatering predictions; these should initially be six-monthly, then annually once the system is fully established.

Monitoring of the dewatering discharge management system.

Mine water balance evaluation, model development and predictive simulations for future water management requirements.
The level of effort required for each stage of mine project development, as outlined above, is specific to each mine and depends on the hydrogeologic conditions encountered. If the project is hosted mostly in low permeability rocks, then it may not be necessary to consider the installation of a test dewatering well. However, even if the rocks are of low permeability, it is important that some form of groundwater stress testing is included in the program as early as possible.

Many mature open pits that undergo expansion and deepening will also require studies to confirm the dewatering and pit slope depressurization steps, needed to support the expansion plan. Significant mine expansion and deepening may change production dewatering requirements, compared to historic operations at the site. Groundwater pumping rates, pumping locations and pumping heads may change. Revision of overall slope angles, increase in overall slope heights and change of ramp configurations, as part of expansion, can create significant increase to the depressurization efforts needed to support the geomechanical performance and slope design.

In a mature mine, expansion studies can be supported by long term production pumping and slope depressurization experience within the existing mine. Further, the exposed pit slopes can provide for access to conduct drainage trials. In many mine expansion situations, work to define dewatering and slope depressurization can commence at the feasibility study level. However, the emphasis remains on developing certainty and confidence through the break-even period of the mine expansion project.

6 Development of an early conceptual groundwater model

A conceptual model of the groundwater system must be developed as early as possible in the planning process, and must be continually updated and refined. The conceptual model forms the basis for underpinning and validating any numerical modeling work. Development of an early understanding brings a cost-effective focus to dedicated hydrogeologic programs implemented during later project development phases.

Most (but not all) mineral deposits contain significant variability in geologic and hydrogeologic condition, tied to lithology, alteration and structural environment. Unless the conceptual model is supported by groundwater response data from multiple locations, rather than only single-well testing results, the results of any numerical modeling work are often subject to an unacceptable uncertainty.

It is usually possible to create the initial characterization of the groundwater system in a cost-effective manner by ‘piggy-backing’ the hydrogeologic data collection program with the mineral and geotechnical drilling. In this way, a valuable hydrogeologic understanding can be obtained of the important controls on groundwater flow, which are typically:

- Zones where groundwater heads (total head measurements) are similar (flat gradients) over a wide area. This often indicates interconnection of the groundwater system, and may indicate the potential for regional-scale groundwater flow.

- Zones where “stair-stepping” of groundwater levels can be correlated with known geological structures. This often provides good evidence of discrete flow barriers and “compartmentalization” of the groundwater system, which may also inhibit the overall required dewatering rate.

- Zones of weak rock and low permeability that may indicate sectors of the mine that require intensive effort to depressurize and stabilize the pit slopes. These can usually be identified with monitoring of water production during the course of drilling or packer testing in appropriately conditioned core holes.
Timing and forward planning of the dewatering program

The conceptual model and the mine plan can be used initially to define target elevations for the dewatering system and the pit slope depressurization program, and to assess the time available to achieve the defined targets.

In a high permeability setting, where removal of significant groundwater flow from operating areas is the main objective, target groundwater levels are set based on maintaining the water table one or more benches lower than the lowest working benches in the mine plan. Relatively simple analysis or the 3D groundwater flow model can be utilized to define pumping rates and well placements required to attain the target groundwater level, to either meet or exceed the rate of vertical mining advance.

For situations where groundwater pressure reduction is required to support slope design and geomechanical performance, setting of targets normally involves defining target pressure distributions and hydraulic gradients throughout the pit slope, which oftentimes may not involve require desaturation of the rock mass. Establishment of groundwater pressure targets requires integration (semi-coupling or one-way coupling) of pit slope pore pressure modeling and geotechnical modeling, in order to determine the pressure regime that supports an acceptable Factor of Safety for a given slope angle, and the amount of time needed for the depressurization measures to attain the target pressures.

The defined dewatering target elevations and mine plans are used as the basis for estimating the range of required pumping rates for LoM dewatering. Typically, when general mine dewatering is required, production dewatering wells and associated infrastructure are constructed at least one to two years in advance of planned mining activity below the groundwater table. In situations where sector-specific depressurization is required, the dewatering measures can often only be implemented concurrent with mine advance, and may be strongly influenced by drill rig accessibility to specific slope sectors. Therefore, advanced pit slope depressurization may only be successful in historic mine operations where poor slope performance and low-permeability conditions have been documented, and where access onto existing slopes is feasible.

Projects in remote areas often require a substantial lead time to mobilize equipment and carry out initial works prior to excavation of the pit. Lead times may be required for procurement and shipping of the necessary equipment. Importation procedures for certain countries may also be a significant factor. Training of personnel in developing countries must also be factored into the overall planning process. Given the lead time for equipment, construction and initial operation to meet targets, the planning process may need to occur a year or more ahead of projects developed in established mining districts.

At times of mining “boom”, even projects in well recognized mining districts may also require advanced planning because of the industry-wide demands on support equipment and personnel. Appropriate drilling equipment, well construction materials and pumping systems regularly involve months of advanced planning, due to delivery lead-time.

In mature large open pits, where major slope depressurization may require underground tunnel drives and drain drilling, the advanced lead time for construction and drain drilling may involve timeframes of three or more years. Examples of such programs include the Highland Boy Drainage Gallery at Bingham Canyon and the North Wall Drainage Tunnel at Escondida.

However, even considering all of the above factors, the most important control for project development is often the ability to gain public confidence and to obtain regulatory approval for the water-related aspects of the project. In many established mining districts throughout the world, the time taken to achieve regulatory approval has increased significantly over the past 10 years or so, and a reasonable time frame to obtain all necessary permitting is now 3 to 5 years. As a result, it is often necessary to “front-load” the early-phase studies to provide sufficient technical support for the required permit applications. Due to the increasingly onerous regulatory process in established mining districts, the time required for project development may be considerably less in countries where external investment and infrastructure-building is actively encouraged.
8 Implementation of a groundwater control program

In settings where a general lowering of the groundwater table around the pit area is required, most open-pit mine dewatering systems use some form of vertical production pumping wells, either external to the pit (outside the crest) or within the pit.

In practice, most mines are located in complex groundwater settings, with a large variability in bedrock conditions, and/or with permeable alluvium and overburden deposits at shallow levels within the slope. Many dewatering projects use a combination of ex-pit wells to intercept and remove groundwater flow that would otherwise enter the pit, and in-pit dewatering wells to remove groundwater storage and accelerate drawdown inside the pit shell.

The interception of groundwater outside of the pit area is advantageous, and should be pursued wherever possible. This reduces the burden of constructing, maintaining and replacing production wells inside the mine operating area, and also minimizes nuisance water inside the pit. Interception of groundwater away from the pit may also lead to an overall decrease in pumping head and pumping costs, even if it is necessary to produce a high volume. In many cases, the operation of ex-pit wells, and particularly alluvial interceptor wells, leads to an overall improvement of the pumped water chemistry, since groundwater is intercepted and pumped before it contacts the mineralized ore deposit. An associated reduction in downstream water management costs may be realized.

The following general types of groundwater control methods are the most commonly used for open pit mining operations:

- **Installation of dewatering wells.** There are many applications for dewatering wells. A classic application involves ex-pit wells used to intercept and remove groundwater through-flow that would otherwise report to the pit, in combination with in-pit wells for removing storage and creating additional drawdown in the operating areas (see Fig. 1).

Figure 1. The typical configuration of drilling equipment utilized for construction of deep, large diameter ex-pit dewatering wells.
- **Installation of pit slope horizontal drains.** Horizontal drains are commonly used in open pits to relieve groundwater pressure behind the pit slopes in rock units that are not amenable to pumping. There are many construction methods for horizontal drains, but a typical construction will involve holes drilled to depths of 400-600 ft, at 4-6 inch diameter, with 1-2 inch diameter slotted pipe installed in the drain.

  Prior to starting a horizontal drain program, it is important to determine the objectives of the drains, and to design the program to accomplish specific targets (see Figs. 2-3). It is often prudent to install the drains at an azimuth such that they intersect the maximum number of joints, fractures and compartments that are tapped by the drains.

- **Installation of “gravity-flowing” vertical or steep angled drains from the pit slope.** Vertical or angled drains can be considered where a large vertical hydraulic gradient is developed within the slope, or where groundwater is perched above a less permeable unit, underlain by more permeable units at depth. The purpose is to cross-connect the low permeability unit that requires drainage to a more permeable zone which is already depressurized.

---

**Figure 2.** Piezometer responses to horizontal drain drilling activity.
• **Implementation of a passive groundwater cut-off system, such as a slurry wall, grouting of permeable fracture systems, or ground freezing.** In an open pit setting, the primary objective is to reduce the permeability of a particular formation or zone along the flow path, with the goal of reducing the amount of groundwater reaching the pit.

Such passive measures are most commonly applied to specific zones within key sectors of the pit, rather than “globally”. However, there are a number of operations currently considering the cost-benefit of a full low permeability “curtain” around the open pit, primarily to meet regulatory constraints.

When considering the application of passive measures, the operator must appreciate that the system will create a “groundwater dam”, such that the total head will not reduce on the outside of the treated area. As a result, there will be a strong tendency for groundwater to find alternatively pathways towards the pit.

• **Use of a drainage tunnel, installed behind the slope or underneath the pit.** Drainage tunnels are being increasingly considered by large open-pit mining projects, both for dewatering and to achieve pit-slope depressurization. Key advantages of a drainage tunnel are that: 1) they can be implemented and operated without interfering with mine operations, 2) they can be constructed earlier in a mine project compared to other measures and pro-actively attain depressurization ‘early on’, and, 3) they can provide permanent access for repeated drilling and drainage of high priority geotechnical zones.

In some settings, where the topography is favourable, gravity tunnels are installed from downslope have been driven below the mine to drain the orebody. There are many examples of this, with some dating back over 100 years. However, in most cases where the goal is to depressurize the pit slopes, the portal of the tunnel is constructed at a convenient location inside the open pit, and the tunnel is driven behind the mine phase(s) of interest, with discharge pumped out via the open pit.
• Implementation of a “do nothing” approach, allowing pressures to dissipate as a result of seepage to the slope, and removal of the water using in-pit sumps. The “do nothing” approach may be applicable in situations where the rock mass in the pit slope has relatively low permeability and is also strong, and there is both: 1) high tolerance to groundwater pressure in the slope design, and, 2) relatively low amounts of groundwater flow and volume entering the pit, and low water impacts to mine operations.

In reality, most large open pit mine projects utilize a combination of the above measures in different sectors, or at different stages of the mine life.

9 Risk factors

For most mining projects, groundwater flow and groundwater pressure provide multiple risk factors that require pro-active management. In most situations, groundwater can be controlled with engineering, so the risk is often economic and pertains to uncertainty related to performance of planned dewatering or depressurization measures.

For a typical large open pit mining operation, the more significant potential risk considerations associated with groundwater, dewatering and slope depressurization commonly include:

• **Down-stream mine water infrastructure** may be inadequate to handle dewatering flows. The consequences of this include the inability to dewater, leading to impacts on mine production, increased operating costs due to the presence of water in the pit, and potentially significant capital to upgrade components of the mine-wide water management system.

• **Permitting constraints** may become more onerous if the initial predictions were not accurate. Higher-than-expected dewatering flows and/or poorer water chemistry can create an excess mine-wide water balance, which may lead to the requirement for a discharge permit which can delay a project and add capital, or may require a water treatment system or other high-cost infrastructure.

• **In-pit production pumping** is often essential to attain dewatering targets but can be challenging to achieve within the operational framework of the pit. Achieving good interaction between “planning” and “operations” is a perennial issue worldwide. It can often lead to regular disruption of access, destruction of wells and in-pit infrastructure, and the inability to carry out the required performance monitoring. Again, the consequences involve inability to accomplish dewatering targets, slowing of mine production and increased stripping and operating costs.

• **Groundwater chemistry or suspended solids** can change with time and create excess wear on dewatering infrastructure. This commonly results in unexpected water treatment costs, or unexpected costs associated with the re-engineering and/or replacement of dewatering infrastructure.

• **Pit slope pore pressure targets** are not attained. As a worst case, the consequences of this are potentially catastrophic. In most cases, the consequence will be the loss of ore resulting from slope re-design (flattening or stepping-in). Failure to reach targets can be caused by many factors including inappropriate timing of active depressurization system implementation, poor design of the depressurization system, or, inability to maintain the system inside the mine operation.

• **A change of mine plan and/or slope design** may put the groundwater control system at risk. This frequently occurs ‘mid-project’ without consideration of the depressurization requirements. Typical pushbacks involve steepening, deepening or acceleration of the pit to gain more ore.
10 Examples of “fit-for-purpose” groundwater management systems

Any mine dewatering or pit slope depressurization system needs to be designed for purpose. It needs to accomplish well-defined targets, and to provide value to the mine plan. These concepts are illustrated below, as three industry examples from the USA:

10.1 Highland Boy Drainage Gallery, Bingham Canyon mine, Utah, USA.

In 2003, Bingham Canyon mine initiated a pushback of west wall of the open pit, a sector known as the “Highland Boy Corner”. Integrated geotechnical and hydrogeologic analysis identified that the overall ultimate slope angle could be steepened by approximately 2 percent with aggressive depressurization of the low permeability intrusive Monzonite rock mass in the lower slope and planned pit floor.

The planned overall slope height for the cut was approximately 2,800 ft and the change in slope angle represented economic variability that justified investment in an underground drainage gallery to depressurize the pushback and allow for the steeper overall slope angle.

The drainage tunnel was constructed between mid 2007 and early 2009. The tunnel was driven from dual portals, for a total of approximately 7,000 ft behind the ultimate planned lower pit slope. Seventeen drill stations were constructed on 100 to 200 ft centers behind the slope sectors requiring depressurization (see Figs. 4-5). Approximately 16 drain holes were drilled from each drill bay, targeting the low permeability rock mass in the planned lower slope and pit floor. The drainage gallery accomplished the depressurization targets required.

Figure 4. Plan view of the ‘Highland Boy Drainage Gallery’ at Bingham Canyon Mine.
10.2 Depressurization of the Trash Dump Slide, Chino mine, New Mexico, USA

In 2006, mining of the southeast wall of the Estrella Pit at the Chino mine experienced significant slope acceleration to the extent that operations were under threat. The results of an integrated geotechnical and hydrogeologic study indicated that a combination of rock strength, structures sub-parallel to the slope, and groundwater pressure were likely contributing to the slope movement. Hydrogeologic testing revealed strong compartmentalization and very low rock mass permeability.

A program of twenty five surface horizontal drains was planned and implemented. The drains were spaced on a tight pattern (50 to 100 ft separation), reflecting the low permeability conditions. They were deliberately oriented into the slope to penetrate and cross the main sub-parallel fault features. Upon drilling of the drains, the slope acceleration dramatically reduced and correlated closely with drain construction. The local mine plan in the vicinity of the slope movement was subsequently accomplished (see Fig. 6).

Figure 6. Prism data from the Trash Dump slide, showing significant slowing after drain installation.
10.3 Dewatering plan at the Ruth pit, Robinson mine, Nevada, USA

Recent expansion of the Ruth pit at the Robinson mine involves a pushback of the southern pit wall through a bounding structural zone and into unaltered carbonate rock. The carbonate sequence is a key component of an extensive regional groundwater system.

Integrated geotechnical and hydrogeological analysis helped to accurately delineate the structural boundary and thus define the target groundwater head in the carbonate rock to meet the pit slope design conditions. The results of the characterization indicated that groundwater heads in the carbonates needed to be lowered by 200-300 ft, requiring a dewatering rate in the range 12,000 to 16,000 gpm. To meet this requirement, test hole drilling and production well construction was initiated in 2007, with the first wells coming on-line in 2007.

Since that time, a total of nine 20-inch diameter, 1,400 ft deep, production dewatering wells have been constructed along the southern perimeter of the pit, providing a pumping capacity of roughly 15,000 gpm.

To date, the water table in the carbonate system has been lowered by just over 100 ft and the model projections indicate that the ultimate drawdown target for the carbonates will be met ahead of the pushback schedule (see Fig. 7). The ex-pit dewatering system minimizes the need for in-pit dewatering efforts and has resulted in effective depressurization of the south pit wall.

Figure 7. Groundwater system piezometric response to dewatering at Robinson.
11 Conclusions

Some form of groundwater control is required at almost all large open pit mining projects at some stage during the mine life. The key factors for designing an appropriate management system vary according to the regional and local hydrogeological setting, the mine plan and the geomechanical nature of the rocks that form the pit slopes. General mine dewatering normally involves pumping from vertical wells to lower groundwater levels and reduce groundwater inflow to operating areas. Pit slope depressurization normally involves some form of drain installation that is geared toward improving the strength of the materials in the slope.

The successful planning and implementation of a dewatering and slope depressurization system can have a significant impact on the economic performance of the mine. For any given mine setting, the correct characterization of the hydrogeological system and definition of the targets for dewatering or slope depressurization is essential to ensure that a “fit-for-purpose” system is designed and implemented.