ENVIRONMENTAL ISSUES ASSOCIATED WITH DEWATERING MINE EXCAVATIONS

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ABSTRACT
An open pit mine, gravel pit or rock quarry are all mine excavations that may require dewatering. Dewatering a mine excavation is necessary to provide dry access to the valuable mineral or aggregate when the excavation extends below the water table. Dewatering is also often required to maintain the stability of excavated overburden and bedrock slopes since hydrostatic pressure acting on a rock or soil slope can result in slope failure. Recognizing that every mine excavation has unique dewatering requirements, this paper will examine some of the common environmental issues associated with mine excavation dewatering and responsible management of the surplus water. Some of the environmental issues that should be considered include the impact of drawing down the local water table and the quality of water being pumped from the excavation. Finally, some mitigation measures for typical environmental impacts associated with mine excavation dewatering will be presented.

RÉSUMÉ
Les mines à ciel ouvert, les sablières et les carrières sont des types d'excavations qui ont fréquemment besoin d'être asséchées. En effet, le pompage des excavations minières est nécessaire afin d'accéder aux minerais ou aux aggregats lorsque ceux-ci se retrouvent sous le niveau de la nappe phréatique. De plus, le pompage permet une plus grande stabilité des pentes d'excavation dans les dépôts meubles et le roc limitant ainsi l'action des pressions hydro-statiques pouvant provoquer des mouvements de masse. Sachant que chaque excavation minière a des besoins particuliers d'assèchement, cet article examine les aspects environnementaux reliés au pompage des excavations minières et une gestion responsable des eaux de pompage. Parmi les aspects environnementaux à considérer, l'abaissement des nappes phréatiques des régions avoisinantes et de la qualité des eaux de pompage constituant les principaux enjeux. Finalement, des mesures d'atténuation des principaux impacts environnementaux associées au pompage d'excavation minière sont présentées.

1. INTRODUCTION

Mining of aggregate or mineral resources requires excavation of overburden and/or bedrock. Excavation is required to expose and access the valuable mineral or aggregate and then to extract the resource for processing and sale.

Mine excavations can be categorized into either surface or underground mines, both of which usually require some form of dewatering. Where it is required, dewatering and responsible water management presents many challenges. Although, this paper will examine dewatering of surface or open pit mines only, it should be noted that dewatering is also an important element of underground mine design and operation.

1.1 Purpose of Mine Excavation Dewatering

Dewatering a mine excavation is necessary to provide dry access to the mineral or aggregate when the excavation will extend below the water table. In addition, dewatering is often required to maintain the stability of excavated overburden and bedrock slopes. Hydrostatic pressure and gravity are the most significant forces acting on a rock or soil slope. According to Piteau (1971), water pressures in rock joints have probably been responsible for more slope failures than all other causes taken together. Optimum open pit mine design requires minimizing the excavation of non-economic overburden and waste rock. This objective can be achieved by excavating the steepest sideslopes possible while maintaining an acceptable minimum factor of safety. For example, a sand slope can be steepened from 15 to 30 degrees (i.e. two-fold increase in steepness) by dewatering. Moreover, a shale rock slope that is stable at an angle greater than 45 degrees when drained is stable at significantly less than 30 degrees when undrained (Piteau 1971). When it is necessary, dewatering ensures the safety of the mine operation and workers. As a result, dewatering is a very critical and important part of a mine operation.

1.2 Objective of the Paper

Recognizing that every mine excavation has unique dewatering requirements, this paper will examine some of the environmental issues associated with mine excavation dewatering and responsible management of the surplus water.

The two most significant environmental effects of dewatering are impacts of water table drawdown and discharge of water being pumped from the excavation. Finally, some mitigation measures for typical environmental impacts associated with dewatering will be presented.

2. EFFECTS OF ACTIVE DEWATERING

Not all mine excavations require dewatering. For example, a gravel pit that does not extend below the water table does not require dewatering. In fact, gravel can be excavted below-water using a dragline excavator to minimize the environmental impacts of dewatering. However, an aggregate quarry being mined in an area with a shallow groundwater table will usually have to be actively dewatered so that blasting and excavation of rock can be done on a dry floor. In this case, dewatering artificially lowers the water table to at least the quarry floor. Although it is possible to blast underwater, below-water extraction of rock is difficult and uncommon.

2.1 Lowered Groundwater Table

Active dewatering usually involves pumping groundwater from inside or outside of the excavation in order to lower the groundwater table in the vicinity of the excavation. The pumping creates a cone of groundwater depression that can extend over a very large area (i.e. several square kilometers). Lowering of the groundwater table is typically the most significant environmental impact of dewatering.

The radius of influence (i.e distance that groundwater table is effected by pumping) and gradient of the drawdown cone (i.e. change in depth of water table with distance from the mine excavation) can be predicted with a hydrogeologic groundwater model. More on predicting the cone of depression and pumping rates is presented in Section 5.1.

2.2 Management of the Surplus Water

The second biggest environmental issue associated with dewatering is responsible management of the large quantity of water pumped from the ground to dewater the excavation. Generally, the shallower a mine excavation the easier it is to dewater. However, it should be recognized that the amount of water flowing into an excavation is a function of both the hydraulic conductivity or transmissivity of the surrounding material and the head difference between the initial water table and the lowered water level.

Deeper mine excavations have a greater head difference and therefore if all other variables remain constant the quantity of water that must be pumped will increase accordingly. The depth of an open pit mine excavation is usually determined by the geometry of the ore body and limited by the economics of overburden and waste rock excavation costs versus the value of the mineral being mined. Some very deep open pit mines have been excavated to extract large, valuable ore bodies. However, it should be realized that there is usually a practical maximum excavation depth from surface for a given ore body.

The water pumped from a mine excavation will be comprised of both surface water and groundwater. Both direct precipitation into the mine excavation and surface water runoff into the excavation should be considered when determining required pumping rates. The contribution of surface water can be significant if proper diversion ditching or drainage control structures are not installed.

A water balance, the sum of all the water inputs (i.e. precipitation, etc.) minus the losses (i.e. evaporation, etc.), can be carried out to assess the impact of dewatering on a watershed. Evaporation from ponds can reduce pumping volumes significantly and should be included in water balance calculations. In addtion, the requirement for on-site water use (i.e. washing plant, etc.) should be considered when estimating discharge quantities. However, it should be noted that wash or process water is often recirculated.

3. ACTIVE DEWATERING METHODS

3.1 Sump-Pump Dewatering Systems

Adequate dewatering of many quarry operations can be achieved by pumping from a central sump located at a low point in the quarry. Pumping from a sump is an effective and simple dewatering technique, if hydrogeological and geotechnical conditions at the site allow (e.g. slope stability is not compromised by seepage from the excavation face). Ongoing operation of the sump pump system will draw down the water table in the vicinity of the mine. Figure 1 illustrates in cross-section how the water table around a mine excavation is artificially lowered by pumping from a central sump located on or below the pit floor.

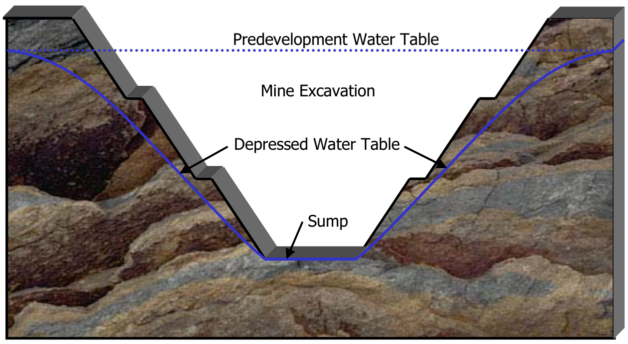

Figure 1. Dewatering by Pumping from a Sump

3.2 Perimeter Well Dewatering Systems

A perimeter well dewatering system involves the installation and pumping of groundwater extraction wells around the perimeter of an excavation to artificially lower the groundwater table within the excavation area. Each well creates a cone of depression, and assuming that the well spacing and pumping rates have been designed properly, ongoing operation of the perimeter wells should artificially lower the water table in the vicinity of the mine. Figure 2 illustrates a mine excavation being dewatered with perimeter pumping wells in cross-section.

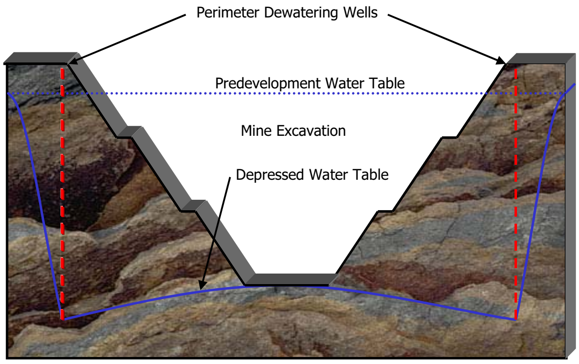

Figure 2. Perimeter Dewatering Wells

4. PASSIVE GROUNDWATER BARRIERS

Although the technical definition of dewatering involves removal of water from the subsurface there are many different methods that involve passive barriers to cut-off groundwater flow into a mine excavation. Passive barrier or cut-off techniques applied to mine excavation dewatering can include grouting, bentonite slurry trenches, and ground freezing. Installation of a passive groundwater cut-off can reduce the radius of drawdown and the water pumping rates from a traditional active dewatering system. Reduced pumping rates save energy and result in smaller discharge volumes (i.e. reduced environmental impact). A brief explanation of these passive barrier techniques follows.

4.1 Grout Curtains

Grouting involves the injection of cementitious or chemical grout into bedrock fractures or granular soil voids to reduce the hydraulic conductivity of the material. Grout is injected under pressure into drilled boreholes at regularly spaced intervals around the mine perimeter to create a grout curtain with reduced permeability. Grout curtains can also be installed in soils to reduce hydraulic conductivity, but are typically more practical for bedrock applications. Depending on the application and design criteria, a single row or multiple rows of grout injection points may be required.

Recent advances in grouting technology, materials and grouting procedures have made grouting karst limestone possible. The high rate of groundwater flow through karst limestone and the presence of large voids can be overcome by injecting low mobility grouts (LMG), polyurethane grout products, hot bitumen, or accelerated cement-based slurries. Specialized grouting techniques were utilized at a limestone quarry with karstic features to successfully cut-off flow from a nearby river (Bruce et al. 2001).

A grout curtain around all or part of the perimeter of a mine can significantly reduce the rate of groundwater flow into the excavation. Used alone or in combination with active dewatering, grouting can be an effective and viable method of maintaining a dry mine excavation.

4.2 Bentonite Slurry Trenches

Bentonite slurry trenches are constructed by backfilling a trench, typically excavated in overburden, with low-permeability benonite-cement slurry. Where practical a bentonite slurry trench should be keyed into the bedrock underlying the overburden to prevent leakage at the overburden/bedrock contact. Bentonite slurry trenches are typically not practical or economic for installation in bedrock.

The bentonite slurry creates a wall of low-permeability material that limits the flow of groundwater into the excavation. Used alone or in combination with active dewatering, a bentonite slurry wall can be an effective and viable method of maintaining a dry mine excavation.

4.3 Ground Freezing

Ground freezing involves the drilling of boreholes and installation of piping that circulates a refrigerated liquid (e.g. coolant or salt brine) to freeze the ground around the pipe. The radius of freezing around a refrigerated pipe is a function of soil type and groundwater flow. The spacing of refrigerated pipes must be determined so that a solid wall of frozen ground surrounds the excavation. Both the installation and operational costs of a ground freezing system should be considered when evaluating this option. Used alone or in combination with active dewatering, ground freezing can be an effective and viable method of maintaining a dry mine excavation.

5. ENVIRONMENTAL IMPACTS OF DEWATERING

5.1 Predicting Drawdown and Pumping Rates

The quantity of water that must be pumped from a mine excavation is a function of the surrounding natural water level, depth of excavation, geology, hydraulic conductivity of the overburden/bedrock, and other hydrogeologic conditions. Equations that calculate discharge from a well point have been derived from Darcy's Law. For example, the discharge from a pumping well in a steady-state, unconfined aquifer can be reasonably predicted with Equation 1 (from Driscoll, 1986). Well discharge equations, however, should not be used to calculate groundwater flow into large excavations as the equations were developed specifically for small diameter well applications.

$$Q = \frac{1.366\ K\ (H^2 - h^2)}{\log R/r} \qquad [1]$$

where :
Q = discharge, in m^3/day
K = hydraulic conductivity, in m/day
H = saturated thickness of the aquifer before pumping, in m
h = depth of water in the well while pumping, in m
R = radius of the cone of depression, in m
r = radius of the well, in m

Analytical calculations should be used cautiously to predict drawdown and pumping rates from a large excavation. Assessment of a multiple-well dewatering system should consider the effects of well interference or drawdown from adjacent wells. Furthermore, surface water infiltration and other important variables are typically not accounted for in most analytical solutions. As a result, groundwater drawdown and pumping rates for a large excavation should be estimated using a two-dimensional finite-element groundwater model as a minimum. A more accurate prediction of groundwater response to dewatering can be made using a three-dimensional groundwater model.

Hydraulic conductivity or transmissivity is the most important variable in predicting drawdown from dewatering. Transmissivity (T) is defined as the product of hydraulic conductivity (K in m/day) and the aquifer thickness (b in m) expressed in square metres per day (m^2/day). The relationship between transmissivity and the cone of groundwater depression can be described as follows; a cone of depression has steep sides and a small radius of influence in an aquifer with low transmissivity, while a cone of depression has flat sides and a large radius of influence in an aquifer with high transmissivity. For a constant pumping rate and other factors, an order of magnitude increase in transmissivity (124 m^2/day to 1,240 m^2/day) results in the radius of influence around a well increasing from about 5,500 m to 12,200 m (Driscoll 1986).

Dewatering first involves removal of the volume of water stored in the predicted cone of depression and thereafter a steady rate of pumping must be maintained to sustain the drawdown. The volume of water in the cone of depression is equal to the product of the cone volume and the void ratio of the dewatered material surrounding the excavation. This volume of water (not including pore water in the volume of excavated rock) can be estimated approximately with Equation 2.

$$V = 1/3\, \pi\, R^2\, s\, e \qquad [2]$$

Where:
V = volume of water in the cone of depression, in m^3
R = radius of influence, in m
s = drawdown depth, in m
e = void ratio of the dewatered material

Table 1 illustrates relative pumping rates (for a single well calculated using Equation 1) required to maintain a certain drawdown in an unconfined aquifer for a range of hydraulic conductivity values. All other parameters have been kept constant for illustrative purposes. As discussed above, it should be noted that Equation 1 calculates flow rate from a single well point and is not suitable for estimating flow rates from a large excavation. Table 1 illustrates that very high pumping rates are required in materials with high hydraulic conductivity.

Table 1. Relative Single Well Pumping Rates for Materials with Different Hydraulic Conductivity Values.

Soil/Rock Type	Hyd. Cond. (m/day)	Rate[1] (m^3/day)	Rate[1] (L/s)
Gravel/Karst Limestone	1.0E+03	3,008,805	34,824
Sand/Karst Limestone	1.0E+02	300,880	3,482
Sand/Karst Limestone	1.0E+01	30,088	348
Sand/Fractured Igneous Rock	1.0E+00	3,009	35
Silt/Fractured Igneous Rock	1.0E-01	301	3
Silt/Fractured Igneous Rock	1.0E-02	30	0
Till/Fractured Igneous Rock	1.0E-03	3	0.03
Clay/Unjointed Sandstone	1.0E-04	0	0.00
Clay/Unfractured Igneous Rock	1.0E-05	0.03	0.00

[1]Calculated for illustrative purposes only using Equation 1 with constant values of H=100 m, h=5 m, R=5000 m and r=0.15 m.

A three-dimensional groundwater model can be used to predict the cone of drawdown and potential impact on adjacent surface water systems and nearby wells. It should be recognized that the ability of a computer model to predict natural system response is limited by the quality of input parameters and should be calibrated with field measurements of response to induced pumping stress. A thorough understanding of the site hydrogeology is therefore required to properly define a groundwater model and predict response to dewatering.

5.2 Impact on Adjacent Wells

Drawdown of the water table as a result of dewatering a mine excavation can conflict with nearby water wells. Adjacent landowners who rely on groundwater for domestic, industrial or agricultural water supply may be affected by lowering of the water table beneath their property. In particular, shallow wells are most at risk of loosing water production capacity or going dry.

Prior to initiating a dewatering program, a baseline survey of all water wells in the vicinity of the mine should be conducted and an assessment of potential impacts to the wells should be carried out. A groundwater monitoring programme will normally be required to assess the impact of the proposed dewatering program. The baseline survey and ongoing monitoring program should assess both the quantity and quality of water in the aquifer of interest.

5.3 Impacts on Adjacent Surface Water Systems

Adjacent wetlands and creeks may be impacted if the cone of groundwater depression extends beneath them. This may result in reduced groundwater discharge to the surface water system causing a reduction in baseflow. Another potential impact is drainage of a surface water system into the underlying drawdown cone resulting in a dry river bed or wetland. Reduced baseflows can result in increased water temperatures and impact cold water fisheries.

Sometimes surface water drainage such as creeks and wetlands are perched on an aquitard that maintains hydraulic separation from the underlying aquifer being dewatered. In this case, the impact of dewatering on the perched surface water systems would likely be minimal. Should a creek be connected to the aquifer being dewatered and the drawdown cone extends below the creek bed then surface water may drain into the drawdown cone resulting in reduced water flow in the creek.

Dewatering and lowering of the groundwater table can cause subsidence of the overburden. Drainage of a soil changes the effective overburden stress and can cause consolidation or subsidence of the ground surface. Changes in elevation across the area of a groundwater depression cone can change the surface drainage patterns and the alignment of creeks.

In addition, discharge of pumped water to a surface water system can impact the system. More discussion on this issue is presented in Section 5.4.

5.4 Management of Pumped Water

Management of the thousands of litres of water pumped from the ground every minute during dewatering can be a challenge. A location suitable for discharging the surplus water is not always readily available. Options include discharge to an infiltration pond, creek, river or lake with sufficient hydraulic capacity to receive the anticipated flows without flooding or erosion. Increased flow rates can affect fish habitat and spawning grounds.

Both the quantity and quality of the water being discharged must be considered when selecting a suitable discharge location. Generally in Ontario, water discharged to a surface water body must meet Provincial Water Quality Objectives (PWQO) which are quite stringent. Other less stringent water quality criteria may apply depending on the proposed discharge location.

Water pumped from a mine excavation can contain dissolved minerals, suspended solids and other contaminants. Water pumped from materials formed in marine environments can be saline. Typically the pH and temperature of groundwater at depth will be different than surface water. In addition, the use of explosives for blasting can increase ammonia concentrations in water pumped from a mine excavation. Water quality (e.g. suspended solids, salinity, pH, temperature, etc.) should be considered when selecting a location for discharge of pumped water. Fisheries habitat are sensitive to temperature and other water quality parameters depending on the species.

Where the receiving water body cannot accept the anticipated quantity and/or quality of the pumped water then a mitigation measure such as treatment in a polishing pond may be required. Some mitigation measures are presented in Section 6 below.

6. MITIGATION MEASURES

6.1 Sedimentation/Polishing Ponds

Prior to discharging pumped water to an adjacent water course, the water quality can usually be improved to the required quality (i.e. receiving water quality) by routing water through a polishing pond. The pond should be designed with sufficient residence time to allow settling of suspended solids. In addition, the pond should have sufficient storage capacity to regulate flow to adjacent surface water systems. Where space and topography permit, a series of ponds can provide more effective removal of suspended solids and polishing. Silt curtains can be used to partition a pond and provide increased residence time for the removal of suspended solids. Settlement of clay-sized particles can be improved by the use of flocculants in the pond, if required.

Typically sedimentation and polishing ponds provide sufficient treatment for discharge of water pumped from a mine excavation and more sophisticated treatment technologies are not required.

6.2 Groundwater Reinjection/Recharge

Groundwater drawdown from pumping can be mitigated by reinjection of groundwater to recharge or raise the water table adjacent to the dewatered mine excavation. Groundwater recharge can be achieved by injection wells or infiltration ponds.

Water pumped from a quarry sump in Ontario has been successfully re-infiltrated into the ground downgradient of a quarry to recharge the water table and prevent impacts on nearby surface water systems (Gartner Lee 2001).

Injection wells or infiltration galleries may require regular maintenance such as backwashing or chemical treatment. With water that is high in iron, the rapid growth of iron-ingesting bacteria can clog the infiltration gallery or well. Inorganic deposits of magnesium, calcium and other ions may also form (Driscoll 1986).

6.3 Surface Water Supplementation

Year-round monitoring of streams, wetlands and other sensitive features should be carried out to accurately predict baseline conditions and any impacts from dewatering.

If drawdown has reduced groundwater discharge to a surface water system, resulting in reduced baseflow, then providing a supplemental supply of water to the surface water system should be considered. Impacts to sensitive vegetation, from a reduction in baseflow, can be mitigated by supplying supplemental water to the impacted area.

Surface water supplementation can be implemented by pumping water directly from dewatering wells or from a polishing pond depending on the quality of water being pumped and the sensitivity of the receiver.

6.4 Use of Passive Groundwater Barriers

Use of passive groundwater barriers can be considered when dewatering will impact adjacent creeks or other water uses. Grout curtains, slurry bentonite trenches and ground freezing (discussed in Section 4 above) are just a few of the available passive barrier technologies that should be considered. The use of other groundwater barrier applications such as a sheet-pile wall (e.g. Waterloo barrier) should be considered for site-specific conditions.

As referenced in Section 4.1, a grout curtain wall that was installed between a limestone quarry in West Virginia and the Shenandoah River successfully cut-off flow from the river into the quarry (Bruce et al. 2001). A sudden inflow of water into the quarry from the nearby river was estimated at over 132,500 L/min and significantly overwhelmed the pumping capacity of the quarry dewatering system. Hot bitumen was injected into karst limestone fractures and voids while cementitious slurry grout was simultaneously injected upgradient. Monitoring of groundwater wells, water levels in the quarry, and flow in the river indicated that flow from the river into the quarry had essentially stopped.

7. PERMITS AND APPROVALS

In Ontario, a Permit to Take Water (PTTW) is required when dewatering will require pumping at a rate greater than about 50 m^3/day (~0.6 L/s). Discharge to surface water will require a Certificate of Authorization (C of A) for Sewer Works Discharge. Approval from the Department of Fisheries and Oceans Canada may also be required where fish habitat is affected by dewatering or discharge activities. Other permits or approvals may be required for other aspects of a mine development project.

8. MONITORING

Monitoring can identify the presence or absence of impact on adjacent natural features and water wells. Furthermore, monitoring is often a common requirement of a PTTW or a C of A for Sewer Works Discharge. In addition, monitoring also provides a means of confirming the effectiveness of mitigative measures. Monitoring programmes should consider seasonal fluctuation and be designed for site specific conditions. Monitoring may include:

- ⇒ Installation of monitoring wells,
- ⇒ groundwater level monitoring,
- ⇒ groundwater quality monitoring,
- ⇒ surface water flow measurements,
- ⇒ surface water quality monitoring, and
- ⇒ fish habitat, benthic surveys, or terresstrial assessments.

Where appropriate, trigger levels or deviations from baseline conditions that may indicate a requirement for mitigation should be defined.

9. WATER MANAGEMENT AFTER CLOSURE

Dewatering will likely cease after the mine is closed. However, water management is an important aspect of mine closure. The long-term effect of any installed mitigation measures and termination of dewatering should be evaluated. Closure of mine excavations must protect public safety and the environment while providing a suitable end use for the property. If required, excavation slopes must be made stable and provisions for protection of public safety must be put in place (i.e. fencing, barricades, signage, etc.). Mine excavations are often allowed to flood after closure to create a lake or recreation area. Interaction of the flooded mine excavation with the surrounding surface water and groundwater systems after closure should be considered.

Ontario Regulation 240/00 amended to O. Reg. 282/03 titled « Mine Development and Closure » under Part VII of the Mining Act dictates mine excavation closure and progressive rehabilitation requirements. Closure and rehabiliation of pits and quarries is regulated in Ontario by the « Aggregate Resources Act ».

10. PLANNING A DEWATERING PROGRAMME

A flow chart or decision tree has been developed (see Figure 3) to assist with planning a mine excavation dewatering programme and assessing potential environmental impacts. Figure 3 provides a framework for identifying potential environmental impacts of dewatering and implementing appropriate mitigation measures.

11. SUMMARY

Dewatering a mine excavation is necessary to provide dry access to the valuable mineral or aggregate when the excavation extends below the water table. Active dewatering usually involves pumping groundwater to lower the water table in the vicinity of the excavation. Dewatering creates a cone of groundwater depression that can extend over a very large area. The two most significant environmental effects of dewatering are impacts of water table drawdown and discharge of water being pumped from the excavation.

Although the technical definition of dewatering involves removal of water from the subsurface, the installation of passive barriers that cut-off groundwater flow to a mine excavation should be considered to reduce the radius of drawdown and water pumping rates. Passive barriers can include grout curtains, bentonite slurry trenches, and frozen ground walls.

Adjacent landowners who rely on groundwater for domestic, industrial or agricultural water supply may be affected by a lowered water table as a result of dewatering. Flow in adjacent wetlands and creeks may be reduced if the cone of groundwater depression from dewatering extends beneath them.

The groundwater pumped from a dewatering system can usually be discharged to an infiltration pond, creek, river or lake. However, both the quantity and quality of the water being discharged should be considered when selecting a suitable discharge location. Where the receiving water body cannot accept the anticipated quantity and/or quality of the pumped water then treatment in a polishing pond may be required prior to discharge.

Another potential mitigation measure is to inject water into the subsurface or encourage infiltration around the quarry to recharge the water table and reduce impacts on nearby surface water systems. If drawdown has reduced flow in an adjacent surface water system then pumping a supplemental supply of water to the affected surface water system could be considered.

Finally, monitoring should be a part of every dewatering programme to verify drawdown predictions, identify any impacts and confirm the effectiveness of mitigation measures.

12. REFERENCES

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Figure 3
Mine Excavation Dewatering Environmental Issues
Planning Decision Tree