# 7.6 Groundwater

Groundwater circulates as part of the hydrologic cycle and can contribute significantly to surface water flow. This section describes the interface of project components with groundwater circulation and quality and the resulting effects on surface water flows and quality and the project water balance. This section refers to climate information described in Section 7.1: Climate. The findings of this section have been integrated into the assessment of surface water flows in Section 7.4: Surface Water Hydrology, Section 7.5: Surface Water and Sediment Quality, and Section 2.9: Site Water Management.

## 7.6.1 Scope of Assessment

### *Issues and Selection of Valued Ecosystem and Cultural Components*

Potential effects of the project on groundwater include:

- interception of groundwater flows by underground mine development with corresponding reductions in groundwater discharge to surface water flows
- effects on groundwater quality due to ARD in the underground mine and mine backfill with associated effects on quality of surface receiving waters
- seepage of contaminated water from the tailings facility, affecting the quality of shallow groundwater flows
- reduction in water table due to well water extraction

The main effect of the project on groundwater flows and quality is related to the underground mine development in the Wolverine Creek watershed. Accordingly the focus of this section is to assess how mine dewatering will alter groundwater levels and quality in the vicinity of the mine, as a basis for determining potential effects on surface water flow and water quality in the Wolverine Creek watershed. Within the exception of the tailings facility in the Go Greek watershed, other potential effects are small, localized and can be readily mitigated. For the Wolverine Creek watershed, all potential effects are characterized and mitigation measures described within this section. All issues pertaining to the effects of the tailings facility on groundwater seepage and quality in the Go Creek watershed are presented in Section 2.8: Tailings Disposal.

Groundwater VECCs were defined for the project environmental assessment based on the EA Report Guidelines (Yukon ECO 2005) and initial findings of field investigations. VECCs for groundwater are selected based on potential project effects and linkages to surface water quality and flows and related effects on other VECCs (water and sediment quality, aquatic biota, fish, wildlife habitat ecosystems). Table 7.6-1 presents a summary of the groundwater VECCs that may be affected by mine dewatering.

### *Temporal Boundaries*

The timeframe for assessing effects of underground mining on groundwater encompasses the period of record for baseline data collection (pre-production underground mine development in 2005), full development of the underground mine during operations (i.e., period of maximum mine dewatering), and closure (i.e., after decommissioning and the restoration of the groundwater table in the mine area). Conditions during each phase are discussed relative to baseline conditions.

### Table 7.6-1 Groundwater VECCs, Selection Rationale and Data Sources

| VECC | Rationale for Selection | Linkage to EA Report Guidelines or Other Regulatory Drivers | Baseline Data for EA |
|---|---|---|---|
| Groundwater quality: pH, conductivity, alkalinity, sulphate, metals, nitrogen compounds (NO3 & NH4) | • Potential for project effects due to underground mine development and associated potential for ARD, metals leaching, and blasting residue affecting groundwater quality<br>• Provides input to characterization of changes in chemical characteristics of surface waters<br>• Provides design parameters for mine water treatment and prediction of effluent quality | • Linked to CCME or other guidelines for protection of aquatic life in surface waters<br>• Monitoring will be required for permitting | • 2005 field data |
| Groundwater flows | • Potential for project effects due to underground mine dewatering, effects on downstream groundwater and surface flows in the Wolverine Creek basin and input of diverted groundwater flows to project water balance<br>• Provides input to characterization of effects on flows and chemical loadings to surface waters<br>• Provides design parameters for mine water pumping and treatment | • Linked to CCME or other guidelines for protection of aquatic life in surface waters<br>• Linked to effects on aquatic habitat in surface waters<br>• Monitoring will be required for permitting | • 2005 field data |

#### *Study Area*

The local study area (LSA) for assessment of effects of the underground mine on groundwater is delineated by the Wolverine Creek watershed. Figure 7.6-1 presents a plan view of the mine groundwater LSA. Groundwater intercepted by underground mine development will be pumped to surface where it will be introduced to the ore processing water balance and treated before being discharged to Go Creek (Section 2.9: Site Water Management). This will result in some water being diverted from the Wolverine Creek watershed into the Go Creek watershed. The assessment of potential changes in surface water flows in Wolverine Creek and Go Creek are discussed in Section 7.4: Surface Water Hydrology.

As no other existing or reasonably foreseeable future developments are known which would result in effects on ground water in the Wolverine or Go Creek drainages, no regional study area for cumulative effects has been defined. A regional study area for effects of the project on surface water flows and quality are detailed in Section 7.4: Surface Water Hydrology and Section 7.5: Surface Water and Sediment Quality.

### Figure 7.6-1 Groundwater – Local Study Area (Vol. 2)

## 7.6.2 Baseline Conditions

### *Bedrock Hydraulic Conductivity*

To characterize the permeability or hydraulic conductivity of the bedrock in the vicinity of the mine, in-situ permeability testing was carried out using an inflatable packer testing apparatus at two exploration borehole locations (herein referred to as PZ-A and PZ-B). Table 7.6-2 describes the details of the exploration boreholes that were part of the hydrogeology characterization program and Figure 7.6-2 illustrates their location in plan view. The boreholes at PZ-A and PZ-B both extended several metres beneath the ore zone to depths of 194.2 m and 198.4 m along the borehole axis, respectively.

Packer testing allows discrete intervals of bedrock within a borehole to be sealed off and tested to measure the permeability of that interval. The packer testing data was analyzed to obtain estimates of hydraulic conductivity of the various bedrock units encountered by each of the exploration boreholes. The results of the borehole packer testing are summarized in Table 7.6-3. Figure 7.6-3 presents a graph of packer test results versus depth below ground surface. Table 7.6-4 presents a summary of inferred hydrostratigraphic units and the assigned hydraulic conductivity values used to develop the conceptual hydrogeologic model for the mine.

### Table 7.6-2 Mine Area Hydrogeology Investigation Borehole Details

| Piezometer Name | Borehole Name | UTM Coordinates (NAD 27) | | Surface Elevation (m asl) | Borehole Length (m) | Borehole Dip (degrees) |
|---|---|---|---|---|---|---|
| | | Northing | Easting | | | |
| PZ-A | WV05-156 (Lynx) | 6811111 | 439851 | 1393 | 194.2 | -75 |
| PZ-B | WV05-155 (Wolverine) | 6810835 | 440085 | 1389 | 198.4 | -85 |

### Figure 7.6-2 Conceptual Hydrogeologic Model Plan (Vol. 2)

### Table 7.6-3 Results of Mine Area Borehole Packer Testing

| Location | Test Number | Packer Test Interval (along borehole axis) | | Calculated Hydraulic Conductivity (cm/s) | Qualitative Description of Hydraulic Conductivity Relative to Other Test Intervals |
|---|---|---|---|---|---|
| | | Top (m) | Bottom (m) | | |
| PZ-A (Lynx) | 1 | 33.5 | 125.0 | $2.62 \times 10^{-6}$ | Average |
| | 2 | 67.1 | 115.8 | $6.59 \times 10^{-7}$ | Less permeable |
| | 3 | 118.0 | 194.2 | $2.18 \times 10^{-6}$ | Average |
| | 4 | 128.0 | 145.4 | $6.84 \times 10^{-5}$ | More permeable |
| PZ-B (Wolverine) | 1 | 73.8 | 156.1 | $7.51 \times 10^{-6}$ | Average |
| | 2 | 117.3 | 156.1 | $1.30 \times 10^{-5}$ | Average |
| | 3 | 135.0 | 156.1 | $3.94 \times 10^{-5}$ | Average |
| | 4 | 150.3 | 156.1 | $1.72 \times 10^{-7}$ | Less permeable |
| | 5 | 74.7 | 83.8 | $1.81 \times 10^{-4}$ | More permeable (i.e., fractured/fault zone) |

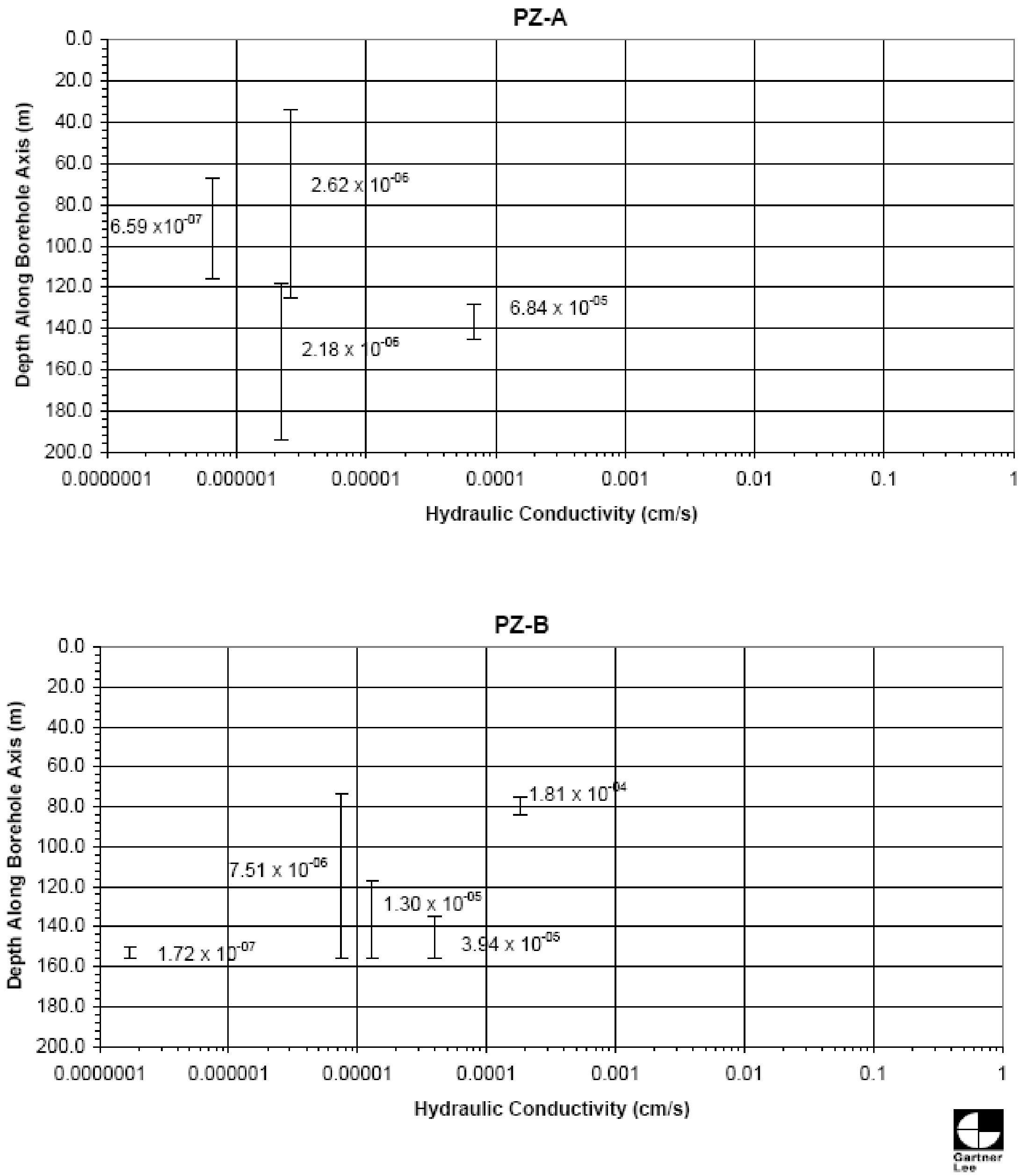


**Figure 7.6-3 Hydraulic Conductivity vs. Depth (plotted over test interval)**

### Table 7.6-4 Summary of Inferred Hydrostratigraphic Units

| Hydrostratigraphic Unit | Composition | Assigned Hydraulic Conductivity (cm/s) |
|---|---|---|
| Overburden | Soil and Talus | $1 \times 10^{-4}$ |
| Weathered bedrock | Rhyolite/Argillite Sedimentary and Volcanoclastic Rocks | $5 \times 10^{-4}$ |
| Host bedrock | Rhyolite / Argillite Sedimentary and Volcanoclastic Rocks | $1 \times 10^{-5}$ |
| Upper iron formation | Exhalites | $1 \times 10^{-6}$ |
| Host bedrock | Rhyolite/Argillite Sedimentary and Volcanoclastic Rocks | $1 \times 10^{-5}$ |
| Lower iron formation | Exhalites | $1 \times 10^{-6}$ |
| Host bedrock | Rhyolite / Argillite Sedimentary and Volcanoclastic Rocks | $1 \times 10^{-5}$ |
| Mineralized zone | Massive Sulphides | $1 \times 10^{-6}$ |
| Host bedrock | Rhyolite / Argillite Sedimentary and Volcanoclastic Rocks | $1 \times 10^{-5}$ |

#### *Conceptual Hydrogeology Model Development*

Geological information for several boreholes was interpreted to form the basis of the conceptual model. The sources of geological information included exploration borehole logs, monitoring well logs, borehole packer testing data, groundwater elevation data, pumping test analysis and topographic mapping. Based on the geological logs and packer testing data, hydrostratigraphic units were identified and assigned hydraulic conductivity values.

Two bedrock aquifers are present in the vicinity of the mine including a shallow unconfined aquifer above the iron formations and a deeper, semi-confined aquifer below the iron formations. Based on hydraulic conductivity data and groundwater elevations recorded during the advancement of the decline during the test mining program, the upper and lower iron formation as well as the mineralized zone behave as aquitards and may slow the flow of groundwater. Groundwater elevations collected during the initial stages of test mining were analyzed using a leaky confined aquifer solution for a homogeneous and isotropic aquifer inferred to be 150 m in thickness. Water table depths and flow divides were inferred based on ground surface topography, surface water bodies and known water table elevations in close proximity to the mine area. Groundwater is inferred to flow from northeast to southwest near the mine as shown in plan on Figure 7.6-2.

A total of four vibrating wire piezometers were installed in two exploration boreholes (PZ-A and PZ-B) during April 2005 to monitor groundwater elevations on an ongoing basis. The vibrating wire piezometers were grouted in place using a cement/bentonite grout mixture so that the piezometers measured groundwater pressure at a discrete point. Vibrating wire piezometer data was used to develop the conceptual model and will continue to be monitored to validate and refine the conceptual model.

Table 7.6-5 summarizes the piezometer installation details and potentiometric elevations measured at PZ-A (Lynx mineralized zone) and PZ-B (Wolverine mineralized zone). The piezometers were located to monitor groundwater conditions in the Lynx and Wolverine mineralized zones at the proposed depth of mining. The piezometer installations were intentionally located just outside of the proposed mine excavation areas between the Lynx and Wolverine zones (PZ-A) and southeast of the Wolverine Zone (PZ-B) so that they will not be disturbed during mining operations and monitoring of these piezometers can continue during mine development and operations. Static, pre-mining groundwater levels range from about 15-20 m below ground surface at instrumented borehole locations PZ-A and PZ-B. A graph of measured potentiometric elevations is presented in Figure 7.6-4. A significant downward gradient was observed at PZ-A in the Lynx Zone and a near neutral gradient was observed at PZ-B in the Wolverine Zone indicating that the mine is located primarily in a groundwater recharge area. PZ-B appears to be located near the groundwater recharge/discharge divide.

### Table 7.6-5 Summary of Deep Bedrock Piezometers and Potentiometric Levels

| Piezometer Name | Ground Surface Elevation (m asl) | Elevation of Shallow Piezometer Installation (m asl) | Elevation of Deep Piezometer Installation (m asl) | Pre-Test Mining Potentiometric Level Measured on July 1, 2005 (m asl) | |
|---|---|---|---|---|---|
| | | | | Shallow | Deep |
| PZ-A (Lynx) | 1393 | 1362.5 | 1243.0 | 1376.89 | 1373.64 |
| PZ-B (Wolverine) | 1389 | 1329.2 | 1280.7 | 1370.01 | 1370.78 |

Precipitation measurements from the on-site climate station (in mm) and qualitative observations of rain (from July 31, 2005 to September 1, 2005, when the climate station datalogger was not operational) are included on Figure 7.6-4. Precipitation data was reviewed in conjunction with the groundwater elevation data to assess the short and long-term response of groundwater levels to precipitation events. Groundwater recharge occurs both within the mine area and upslope of the proposed mine footprint (i.e., northeast of the mine). Groundwater discharge to Wolverine Creek occurs downgradient (i.e., southwest) of the proposed mine area along the upper 1 km reach of the creek adjacent to the mine. Precipitation and piezometer data indicates that groundwater levels (and resultant inflow rates into the mine workings) may vary in response to seasonal fluctuations in precipitation and infiltration. The piezometer measurements indicate that groundwater elevations at these depths do not fluctuate on a short-term basis in response to infiltration or rainfall events; however a response to seasonal trends in precipitation and infiltration was observed. Although small fluctuations in water pressure could be a result of variations in barometric pressure, the significant depth of the piezometers probably dampens and/or removes any barometric pressure effects. Temporary increases in porewater pressure and then recovery to initial levels may have been caused by blasting or construction activities during test mining. There appears to be a seasonal decline in water levels (i.e., not mining related) at all piezometer locations and depths between June and August 2005 indicating that groundwater levels naturally drop during the summer season and that summer is not a period of groundwater recharge. The deep piezometer at PZ-B appears to have responded to dewatering activity during test mine decline development being carried out approximately 160 m from the piezometer. However, the shallow piezometer at this location had not yet responded to the dewatering. This indicates that the upper and lower aquifers are separated by a semi-confining or confining layer (i.e., the iron formation). Artesian groundwater conditions (i.e., water pressures above ground surface) were measured in a standpipe piezometer screened in bedrock adjacent to Wolverine Creek (MW05-3A described in Section 2.8: Tailings Disposal) confirming that the area between the proposed mine and Wolverine

Creek is a groundwater discharge area. Ongoing monitoring of the mine area piezometers will confirm what effects are seasonal what effects are mine dewatering related.

Inferred pre-mining groundwater flow conditions are presented in cross-section on Figures 7.6-5 and 7.6-6. Precipitation on the ground surface above the mine infiltrates into the ground and recharges the groundwater flow system. Groundwater flows southwestward to discharge locations along Wolverine Creek.

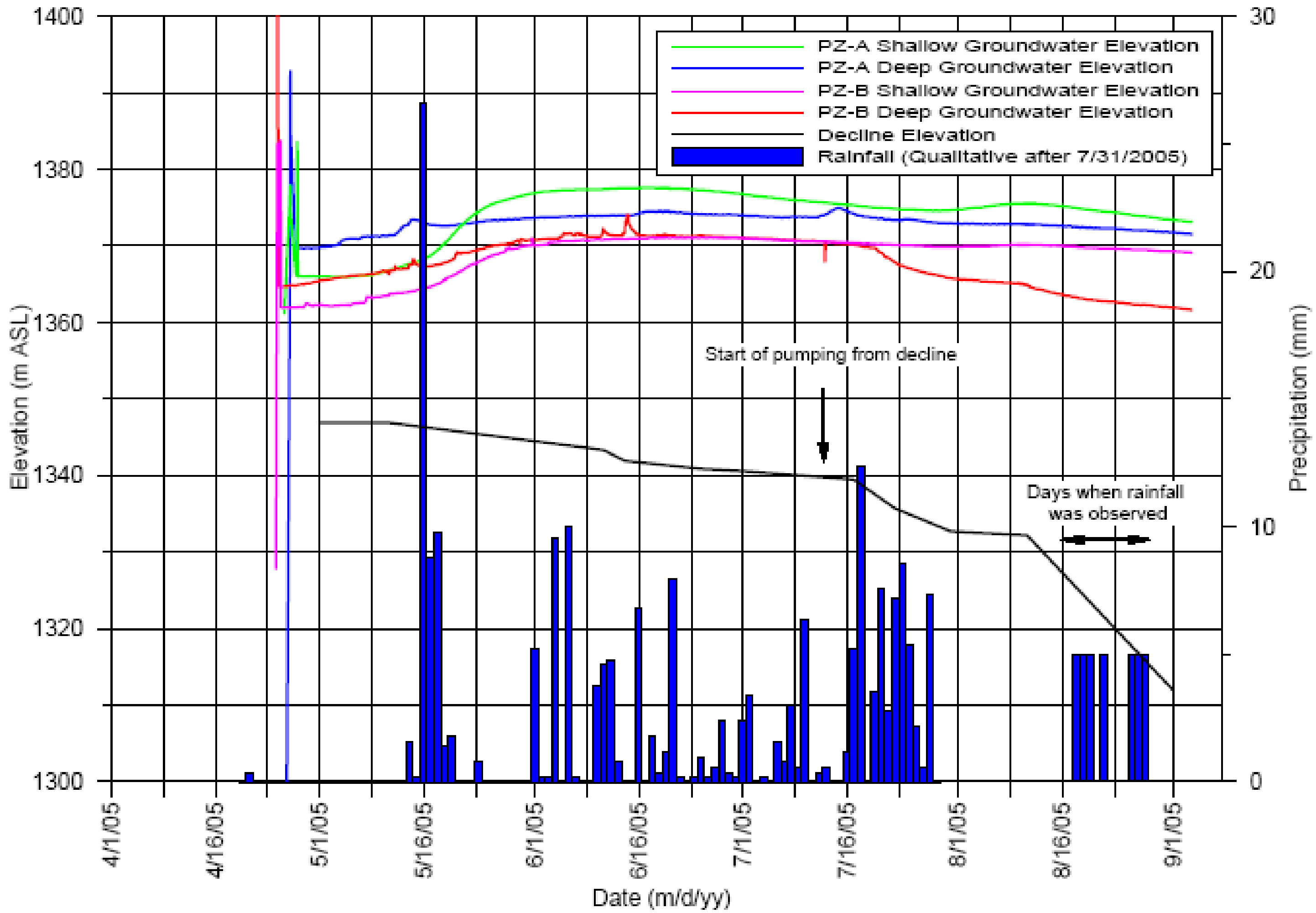


**Figure 7.6-4 Measured Potentiometric Groundwater Elevations in Mine Area Piezometers – Relative to Decline Advancement and Precipitation**

**Figure 7.6-5 Conceptual Hydrogeologic Model Cross-Section A-A' (Pre-Mining) (Vol. 2)**

**Figure 7.6-6 Conceptual Hydrogeologic Model Cross-Section B-B' (Pre-Mining) (Vol. 2)**

***Groundwater Quality***

Groundwater samples were collected from both exploration boreholes and the underground workings during the advancement of the decline. Groundwater samples were collected via exploration boreholes that were approximately 200 m deep using disposable plastic bailers. Boreholes were developed by removing all standing water in the open boreholes using a core barrel on a wireline as a bailer through a length of drill rods.

A summary of groundwater quality results from both boreholes and the portal face, that exceeded Canadian Council for Ministers of the Environment (CCME) Canadian Water Quality Guidelines for the protection of aquatic life are presented in Table 7.6-6. Appendix 7.6-1 provides a summary of all baseline groundwater quality results. The results indicate that baseline concentrations of mineral ions and dissolved metals are relatively low in groundwater in the proposed underground mine area, with conductivity values of 145-389 μS/cm and neutral pH values of 7.7-8.2.

## Table 7.6-6 Summary of Mine Groundwater Quality Exceedences

| | Baseline Groundwater Quality Sampling | | | | | | | | | | | Applicable Criteria |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sample ID** | Lynx PZ-A GW1 | Wolverine PZ-B GW1 | Wolverine PZ-B GW2 (Duplicate) | UG Portal Face | UG Portal Face | UG Portal Face | UG Portal Face | UG Portal Face | UG Portal Face | UG Portal Face | UG Portal Face | CCME – Aquatic Life |
| **Date Sampled** | 4/25/2005 | 4/21/2005 | 4/21/2005 | 6/16/2005 | 7/7/2005 | 7/11/2005 | 8/6/2005 | 8/11/2005 | 8/17/2005 | 8/27/2005 | 8/29/2005 | |
| **Sample Origin** | Borehole | Borehole | Borehole | Decline at ~1343 m ASL | Decline at ~1340 m ASL | Delcine at ~1338 m ASL | Decline at ~1327 m ASL | Decline at ~1325 m ASL | Decline at ~1322 m ASL | Decline at ~1316 m ASL | Decline at ~1314 m ASL | |
| **Approximate Depth (m bgs)** | 150 | 108 | 108 | 4 | 7 | 9 | 20 | 22 | 25 | 31 | 33 | |
| | | | | | | | | | | | | |
| Fluoride F | *0.162* | 0.094 | 0.105 | *0.342* | *0.202* | - | *0.168* | *0.183* | *0.181* | *0.180* | - | 0.120 [1] |
| Cadmium D-Cd | *0.00118* | <0.000050 | <0.000050 | <0.000050 | <0.000050 | *0.000076* | <0.000017 | <0.000017 | *0.000079* | <0.010 | <0.010 | 0.000017 |
| Copper D-Cu | *0.0165* | *0.0024* | *0.0029* | 0.0011 | <0.0010 | <0.0010 | <0.0010 | <0.0010 | 0.0011 | <0.010 | <0.010 | 0.002 – 0.004 |
| Iron D-Fe | *1.5* | *0.656* | *0.836* | 0.142 | <0.030 | 0.032 | *0.433* | <0.030 | *0.937* | 0.142 | 0.076 | 0.3 |
| Lead D-Pb | *0.00136* | *0.0108* | *0.0233* | <0.00050 | <0.00050 | <0.00050 | <0.00050 | <0.00050 | *0.00112* | <0.050 | <0.050 | 0.001 – 0.007 |
| Selenium D-Se | *0.0107* | <0.0010 | <0.0010 | *0.0017* | <0.0010 | <0.0010 | <0.0010 | <0.0010 | <0.0010 | <0.20 | <0.20 | 0.001 |
| Zinc D-Zn | *0.211* | 0.0227 | 0.0176 | <0.0050 | <0.0050 | <0.0050 | <0.0050 | <0.0050 | 0.0193 | 0.0214 | <0.0050 | 0.03 |

**Notes:**
“mbgs” refers to metres below ground surface.
“<” indicates result is less than the detection limit.
“*italics*” Exceeds CCME guidelines for the protection of aquatic life.
All results are expressed as milligrams per litre except where noted.
PZ-B GW2 is a blind duplicate of PZ-B GW1.
1 Guideline for inorganic fluoride

Based on an evaluation of water quality parameters including total and dissolved organic carbon, it is believed that the samples may be slightly affected by surface water used during drilling. Elevated total organic carbon concentrations were present in the samples, which are more characteristic of surface water and shallow groundwater and are not expected to be present in deep groundwater samples. Groundwater quality samples collected from PZ-A and PZ-B represent a blend of deep bedrock groundwater with likely some shallow groundwater introduced during drilling. Groundwater samples collected from underground during test mining (i.e., from the portal face) may be more representative of baseline groundwater quality. Samples collected from shallow underground seeps likely represent shallow baseline groundwater quality with some possible minor impacts to water quality resulting from test mining processes including drilling and blasting. Water quality samples collected from the test mining decline at depth represent the average chemistry of the mine groundwater quality discharging to the test mine working face in August and September and may have also been affected by test mining processes including drilling and blasting.

Major ion chemistry indicates that calcium dominates over sodium, magnesium and potassium which is consistent with the presence of carbonate bedrock. Magnesium concentrations are fairly low and indicate some dilution by surface water used for underground drilling. Elevated concentrations of boron at Wolverine (PZ-B) were two orders of magnitude higher than concentrations observed at Lynx (PZ-A). The differences in water quality between samples collected at PZ-A, PZ-B and underground portal face are likely attributable to variations in geology and the spatial variability of minerals in the vicinity of the two boreholes and the decline ramp.

Trace dissolved metals of interest include selenium, lead, zinc, cadmium and copper. Selenium concentrations exceed CCME guidelines at PZ-A, but remain below detection limits at PZ-B. Lead concentrations marginally exceed CCME guidelines at PZ-A and significantly exceed CCME guidelines at PZ-B. Zinc concentrations exceed CCME guidelines at PZ-A, with concentrations below guidelines at PZ-B, further illustrating the spatial variability of water quality. Elevated cadmium concentrations at PZ-A exceed CCME guidelines while cadmium concentrations are below detection limits at PZ-B. Copper concentrations are approximately one order of magnitude greater at PZ-A than at PZ-B and are well above CCME guidelines at PZ-A and marginally exceed CCME guidelines at PZ-B.

Aluminum concentrations in baseline groundwater samples are below the CCME criteria of 0.100 mg/L. Iron concentrations exceed the CCME criteria of 0.3 mg/L at PZ-A, PZ-B and several underground portal face samples (criteria currently under review).

Elevated pH, conductivity, alkalinity and hardness were observed in samples collected at the portal face during decline advancement, indicating some minor effects of underground test mining and grouting activities on groundwater in contact with rock at the working face.

### 7.6.3 Effects Assessment Methodology

#### *Mine Groundwater Inflow Assessment Methodology*

Groundwater extraction to dewater the mine workings will result in a lowered groundwater table in the vicinity of the mine and may result in reduced groundwater discharge to adjacent surface water systems. Baseline conditions representing pre-mining groundwater levels were quantified and groundwater levels during mine operation were predicted based on typical groundwater response, bedrock hydraulic conductivity, site geology, topography and available groundwater monitoring data.

Based on an understanding of the mine area hydrogeology, the response of groundwater to mine dewatering was predicted by developing a conceptual groundwater flow net and other analytical techniques. The conceptual hydrogeologic flow net representing pre-mining conditions (Figures 7.6-5 and 7.6-6) was modified to represent inferred groundwater levels when the mine is fully developed and the rock above the mine is dewatered. Full mine development and drainage of the overlying bedrock is considered the worst case scenario for potential interception and diversion of groundwater flows from the Wolverine Creek watershed. Figures 7.6-7 and 7.6-8 illustrate the expected groundwater level, equipotential lines and inferred groundwater flow pathways when the underground mine is operational and developed to its maximum depth, at sections intersecting PZ-A and PZ-B respectively.

**Figure 7.6-7 Conceptual Hydrogeologic Model Cross-Section A-A' (Operating) (Vol. 2)**

**Figure 7.6-8 Conceptual Hydrogeologic Model Cross-Section B-B' (Operating) (Vol. 2)**

An estimate of groundwater seepage into the mine was carried out using an analytical equation developed by Goodman et. al. (1965) that relates inflow rate to length of mine drift advanced (Figure 7.6-9). Dewatering data collected during initial advancement of a test mining decline was interpreted as a pumping test to:

- provide a quantitative assessment of aquifer properties
- calculate the expected radius of influence
- estimate potential mine inflows

Appendix 7.6-2 includes a summary of pumping rates and mine dewatering volumes during test mining decline advancement, respectively.

A flow net analysis was carried out to assess potential impact on groundwater discharge to Wolverine Creek from dewatering of the upgradient mine area. This assessment took into account groundwater conditions during both the pre-mining and operational phases as well as creek elevations inferred from topography.

Post-closure groundwater conditions are expected to return to near pre-mining levels (Figures 7.6-2, 7.6-5 and 7.6-6) based on the geometry of the proposed mine development and portal elevation. Furthermore, the mine will be backfilled with loose waste rock and paste backfill (i.e., cemented tailings) and the portal will be sealed at closure, both of which should contribute to post-closure groundwater levels returning to near pre-mining levels. The proposed mine portal (i.e., current test mining portal) is above the elevation of the mineralized zone and proposed mine workings. In addition, the mine portal is above the pre-mining groundwater table elevation. As a result, groundwater should not discharge to surface from the mine portal following closure of the mine.

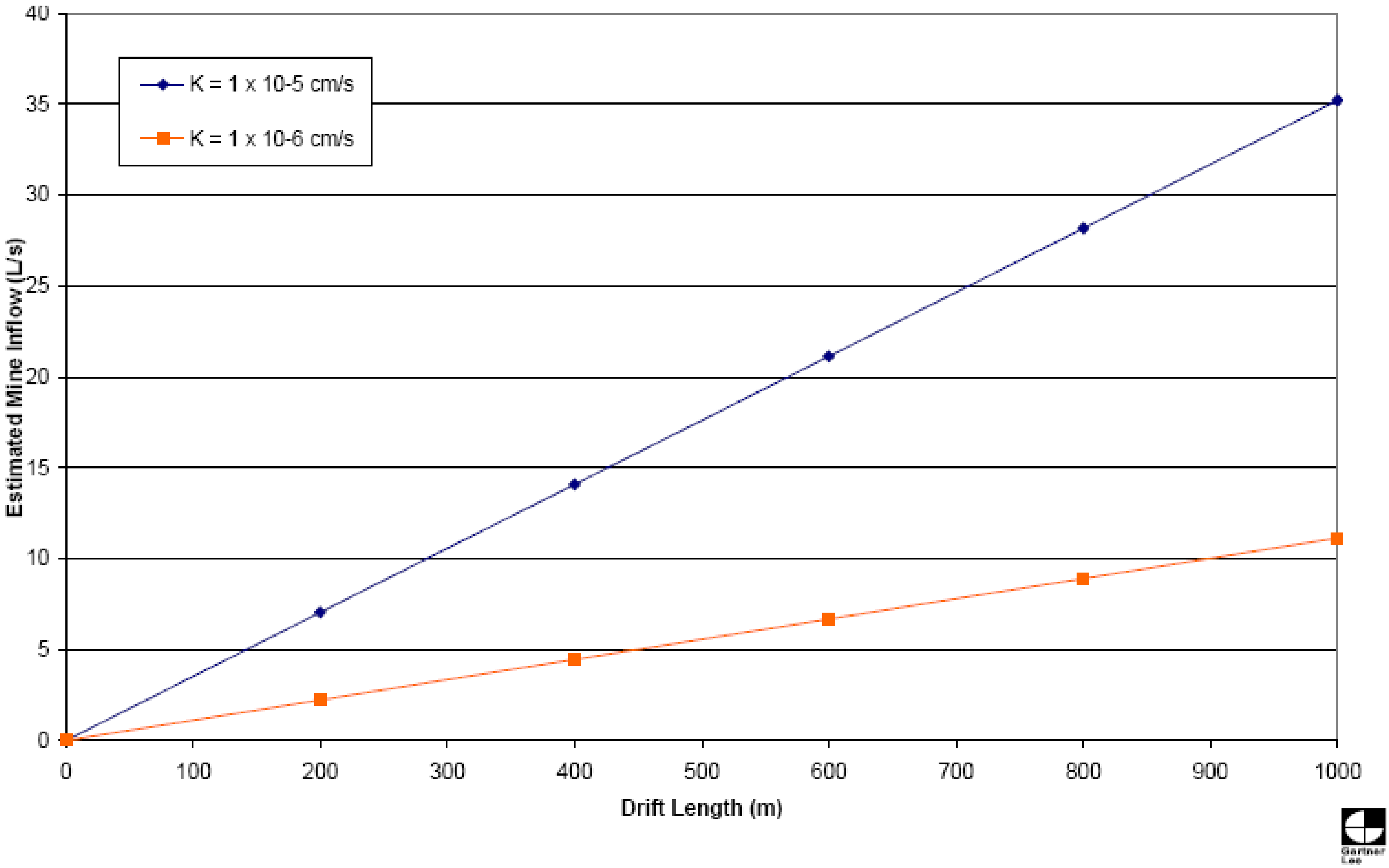


**Figure 7.6-9 Mine Inflow Estimate vs. Drift Length (after Goodman et al. 1965)**

#### *Groundwater Quality at Closure*

A preliminary assessment of water quality of the mine at closure suggests that zinc levels may reach 0.6 mg/L in the mine water following flooding (Section 2.4: Rock Characterization). Although the estimate was developed using a limited amount of geochemical data and gross estimates of the mine geometry and volumes, it does indicate that the post-closure mine water may be adversely effected as the mine floods due to the release of soluble metal complexes on mine surfaces. Other metals may be similarly elevated, but insufficient data presently exists to fully assess the possibility.

#### *Effects Attributes for Groundwater*

Residual project and cumulative effects on water and sediment quality are characterized using effects attributes defined in Table 7.6-7. Groundwater levels will affect surface water flow and water quality, which are discussed in Section 7.4: Surface Water Hydrology and 7.5: Surface Water and Sediment Quality. The ecological, economic and social contexts of effects in groundwater are reflected in the attributes for magnitude of effects on surface water flows, water and sediment quality, and associated effects on aquatic biota, fish and wildlife.

#### *Determination of Effects Significance for Groundwater*

A residual project effect on groundwater will be considered significant if there is an adverse effect of high likelihood, moderate to high magnitude, local to regional in geographic extent and irreversible.

The significance of project effects on groundwater will also be reflected in the determination of effects significance for other VECCs including surface water quality, hydrology, aquatic resources and wildlife.

## 7.6.4 Project Effects

### 7.6.4.1 Operations

#### *Effect of Mine Dewatering on Wolverine Creek Basin*

An analytical equation developed by Goodman et al. (1965) predicted a mine inflow rate of about 10 L/s following development of 300 m of mine drift (i.e., after first year of mining) where the pre-mining groundwater elevation is about 175 m above the average mine elevation (Figure 7.6-9). Development of conceptual hydrogeologic flow net models and interpretation of dewatering data collected during initial advancement of the decline confirmed that a groundwater inflow rate of at least 10 L/s could be expected at full mine development. Inflow rates may be higher immediately following excavation and should decrease with time as the saturated rock above the mine is drained. Figure 7.6-10 illustrates the relationship between inflow rate in L/s and the time to dewater the porewater in the drawdown cone above the mine (calculated to be about 3,000,000 $m^3$). The likelihood of a high magnitude inflow (100 L/s) is considered unlikely indicating that the porewater above the mine will take more than 1 year to drain. An inflow rate of 10 L/s corresponds to a period of 10 years to drain the porewater above the mine.

## Table 7.6-7 Effects Attributes for Mine Groundwater Extraction

| Attribute | Definition |
|---|---|
| **Direction** | |
| Positive | N/A |
| Adverse | Large flow of water into the mine and reduced groundwater discharge into surface streams. Change in groundwater quality causing deterioration of surface water quality |
| Neutral | No change in groundwater discharge rate to surface streamflows; no effects on surface water quality |
| **Magnitude** | |
| Low | Flow: 1L/s<br>Quality: Change in groundwater quality does not have a measurable effect on surface water quality |
| Moderate | Flow: 10L/s<br>Quality: Change in groundwater quality results in measurable effect on surface water quality variable but change does not exceed threshold level (CCME water quality guideline) |
| High | Flow: 50L/s<br>Quality: Change in groundwater quality results in measurable effect on surface water quality variable which exceeds threshold level (CCME water quality guideline) |
| **Geographic Extent** | |
| Site-specific | Effect confined to localized reach of affected stream |
| Local | Effect extends the length of the affected stream |
| Regional | Effect extends downstream of directly affected drainage |
| **Duration** | |
| Short term | Less than 1 year |
| Medium term | 1 to 5 years |
| Long term | Mine operating period and immediately after closure |
| Far future | Following closure and/or permanent |
| **Frequency (Short Term duration effects that occur more than once)** | |
| Low | Frequency within range of annual variability and does not pose a serious risk to the VECC or its economic or social/cultural values |
| Moderate | Frequency exceeds range of annual variability, but is unlikely to pose a serious risk to the VECC or its economic or social/cultural values |
| High | Frequency exceeds range of annual variability and is likely to pose a serious risk to the VECC or its economic or social/cultural values |
| **Reversibility** | |
| Reversible | Effects on VECC will cease during or after the project is complete |
| Irreversible | Effects on VECC will persist during and/or after the project is complete |
| **Likelihood of Occurrence[1]** | |
| Unknown | Effect on VECC is not well understood and based on potential risk to the VECC or its economic or social/cultural values, effects will be monitored and adaptive management measures taken, as appropriate |
| High | Effect on VECC is well understood and there is a high likelihood of effect on the VECC as predicted |

**Notes:** 1 This attribute characterizes the likelihood that the effect will occur as predicted and as characterized by the effects attributes based on status of scientific or statistical information, experience and observations of similar cause/effect relationships and/or professional judgment of the author.

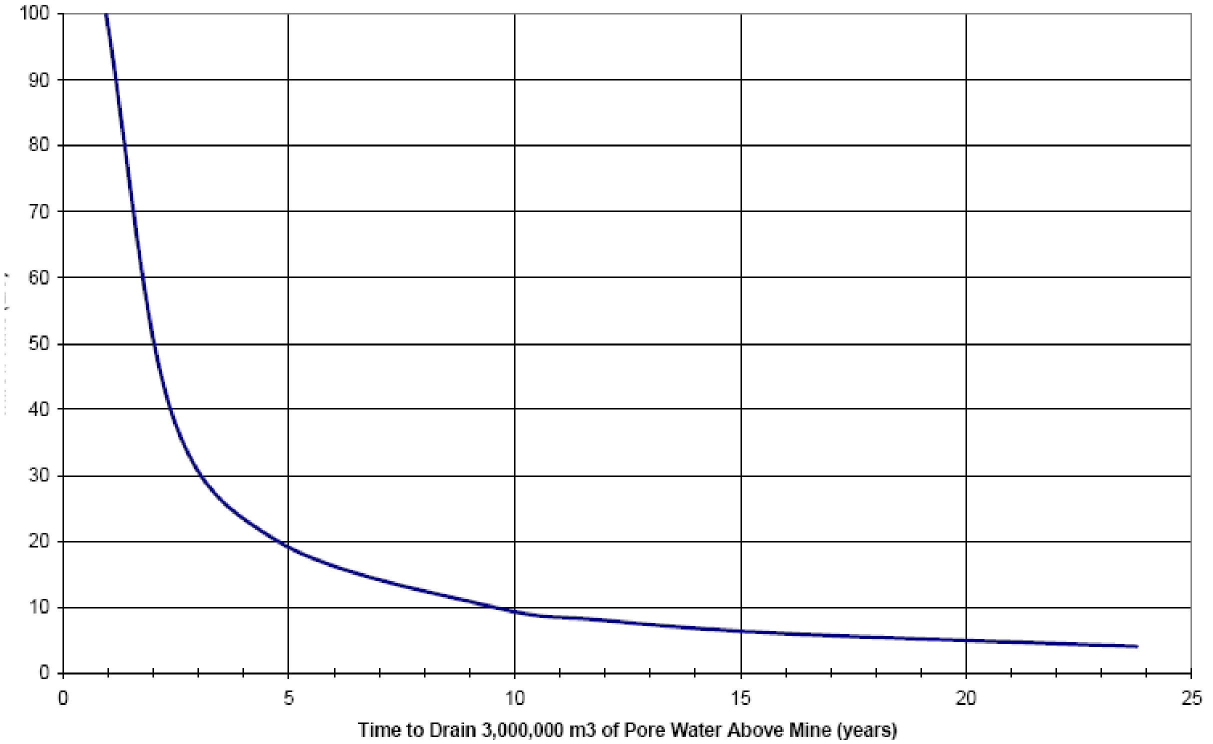


**Figure 7.6-10 Days to Drain Pore Water above Mine vs. Inflow Rate**

Figure 7.6-11 presents a plan view of the potential area of groundwater depression and approximate contours of groundwater levels for the fully dewatered condition (corresponding to groundwater levels illustrated in section on Figures 7.6-7 and 7.6-8). The potential surface area affected by a lowered groundwater table is approximately 0.85 $km^2$. This represents about 50% of the 1.7 $km^2$ Wolverine Creek watershed area.

**Figure 7.6-11 Potential Groundwater Depression Plan (Vol. 2)**

After the rock above the mine is drained and a cone of depression (i.e., lowered groundwater table) has developed around the dewatered mine area then infiltration from precipitation will continue to provide inflow to the mine workings. The minimum rate of mine water inflow from precipitation infiltration is estimated to be about 7 L/s.

Based on the results of a flow net analysis, potential groundwater discharge to Wolverine Creek from the upgradient mine area is estimated to be about 8 to 10 L/s. This will likely result in a corresponding reduction in groundwater discharge to Wolverine Creek.

Based on the elevation of water in Wolverine Creek adjacent to the mine (~1330 m), and the elevation of Little Wolverine and Wolverine Lakes (~1124 m), dewatering of the mine workings (ranging in elevation from 1050 m to 1300 m) is not expected to create gradients that could result in drainage of the lakes into the mine. Dewatering of the mine is not expected to affect water levels in the adjacent Little Wolverine and Wolverine Lakes.

There is a high likelihood of groundwater seepage (10 L/s on average) into the mine that will be pumped to surface resulting in a lowered groundwater table in the Wolverine Creek basin. The lowering of the groundwater table in the mine area and corresponding reduction in discharge to Wolverine Creek during operations is an adverse effect of moderate magnitude, site-specific in extent (the upper 1 km reach of Wolverine Creek, below the proposed mine development), long-term in duration and reversible when the mine is closed and dewatering ceases.

As noted above, groundwater inflow rates may be higher than the projected average immediately following excavation. Such an occurrence would be an adverse effect, of potentially high magnitude, local in extent, short-term in duration and reversible.

Ecological, social and cultural context for effects on groundwater relate to associated effect on surface water quality and aquatic habitat. Potential reductions in groundwater discharge to Wolverine Creek may reduce productive habitat in lower Wolverine Creek during low flow periods and in winter. Section 7.4: Surface Water Hydrology and Section 7.8: Fish Resources assess potential effects flow and fish habitat in Wolverine Creek.

#### *Mine Water Quality*

Mine water may have increased metal concentrations as a result of acid rock drainage and metal leaching from the underground mine workings (Section 2.4: Rock Characterization). Elevated hydrocarbon concentrations are expected from the use and maintenance of mechanized mining equipment underground and fuel oil in explosives. In addition, mine water will likely be affected by residual nitrogen in the form of nitrates or nitrites from ammonium-nitrate-based explosives. The use of cement in paste backfill and for mine excavation support (i.e., shot-crete) may have an effect on mine water chemistry by increasing pH levels (i.e., increase alkalinity). Impacted mine water will be pumped to surface and treated, however during closure pumping will cease and the mine workings will flood. No impacts to mine area groundwater quality are expected during the operations phase (Section 2.9: Site Water Management and Section 7.5: Surface Water and Sediment Quality).

### 7.6.4.2 Closure

#### *Groundwater Flows in Wolverine Creek Basin*

Decommissioning of the underground mine operations will involve plugging the portal entrances and vent raises. The mine workings will be progressively backfilled during operations with cemented tailings (i.e., paste backfill) and loose waste rock, which will likely have a lower hydraulic conductivity than the host bedrock and may create preferential flow pathways. However, the hydrogeology of the mine area will continue to be influenced significantly by the iron formation units. During the closure phase, the mine workings will flood and the groundwater table in the mine area is expected to slowly return to pre-mining levels. Based on a total volume of 500,000 $m^3$ of mine and backfill void space and an additional 2,800,000 $m^3$ of drained bedrock voids above the mine, it could take about 2.5 years to flood the mine after closure and an additional 13.5 years for groundwater levels around the mine to return to pre-mining conditions.

Therefore, it could take up to 16 years following closure (i.e., cessation of mine dewatering) for groundwater levels to return to pre-mining conditions.

The reduction of flow in Wolverine Creek is discussed in Section 7.4: Surface Water Hydrology.

#### *Groundwater Quality*

Groundwater flow through the backfilled mine workings could provide a source of elevated metal concentrations in groundwater, however the use of alkaline materials in the backfill (i.e., lime in cement) should buffer any oxidation of sulfides and contribute to precipitation of dissolved metals (Section 2.4: Rock Characterization). Although, groundwater is not expected to discharge from the portal following closure, groundwater that has passed through the backfilled mine workings will ultimately discharge via the groundwater flow system to Wolverine Creek. A potential residual project effect is discharge of metal contaminated groundwater at closure, to surface water systems including Wolverine Creek, which discharges to Little Wolverine Lake. Groundwater travel times from the mine to surface at Wolverine Creek were estimated to range from 13 years at shallow depth (i.e., shorter groundwater flow path distance) to 52 years for the lowest mine elevation (i.e., longest groundwater flow path distance). Travel time estimates were calculated assuming a bedrock hydraulic conductivity of $1 \times 10^{-5}$ cm/s and a porosity of 5%.

As noted above, the addition of lime to backfill materials is expected to reduce mobilization of dissolved metals in groundwater. In addition, the long groundwater flow path with the possibility of dilution from groundwater recharge outside of the mine working may dilute the potential effects of contaminated groundwater discharge to surface waters. On this basis the effect of discharge of potentially contaminated groundwater on receiving water quality conditions in Wolverine Creek and possibly Little Wolverine Lake is expected to be adverse, of low to moderate magnitude, local in extent, far future in duration and ultimately reversible.

Although the discharge of potentially contaminated groundwater to surface waters is considered likely after the cessation of mine dewatering, the likelihood of a measurable adverse effect on surface water quality in Wolverine Creek is unknown. Portions of the mine will be decommissioned during operations, which will afford an opportunity to monitor groundwater quality in the vicinity of the backfilled areas during operation. Results of paste backfill testing (see Section 2.4: Rock Characterization) and monitoring will provide insight into the effectiveness of the lime additions and saturation of the backfill in managing ARD and metal leaching. Adaptive management measures will be implemented as necessary and monitored. Based on the results of operations phase monitoring, post-closure monitoring may be required to confirm effectiveness of mine backfill in managing groundwater quality at closure.

### 7.6.4.3 Residual Project Effects and Significance

#### *Groundwater Flow*

Adverse residual project effects on groundwater will include reduced groundwater table and corresponding reduction in groundwater discharge to Wolverine Creek during operations. At closure the groundwater table will raise to saturate the backfilled underground mine workings. Water table levels are expected to return to pre-mining levels within 16 years of mine decommissioning, at which time groundwater discharges to Wolverine Creek are expected to approximate pre-mining conditions.

The residual project effect of mine dewatering on groundwater in the Wolverine Creek basin is therefore characterized as moderate magnitude, site-specific (the upper reach of Wolverine Creek, below the mine workings), far future and reversible when groundwater tables are restored. Based on the criteria defined in Section 7.6.3.2, residual project effects on groundwater flows in the Wolverine basin are determined to be not significant.

The ecological, social and cultural context of effects for groundwater relate to associated effects on aquatic habitat. Follow-up studies outlined in Section 7.8: Fish Resources will improve understanding of these effects and the requirement for contingency measures, if any.

***Groundwater Quality***

Residual adverse project effects on groundwater quality in the Wolverine Creek basin are characterized as low to moderate magnitude, local (Wolverine Creek and possibly Little Wolverine Lake), potentially far future and ultimately reversible. Mitigation measures such as lime addition to paste backfill and the long groundwater flow paths are expected to reduce and attenuate potential effects. Monitoring of groundwater quality in backfilled mine workings during operation will provide evidence of mitigation effectiveness and trigger adaptive management as necessary in order to achieve acceptable ground and surface water quality conditions. Based on the criteria defined in Section 7.6.3, residual project effects on groundwater flows in the Wolverine basin are determined to be not significant.

The ecological, social and cultural context of project effects on groundwater quality relate to associated effects on surface water quality and aquatic habitat. Groundwater quality monitoring in backfilled sections of the mine will provide the first indication of potential effects on surface water. If elevated concentrations of contaminants are noted, a corresponding surface water monitoring program will be initiated in Wolverine Creek during operations. Monitoring results will improve understanding of potential effects on aquatic habitat and the requirement for contingency measures, if any, to ensure acceptable water quality for protection of aquatic life in Wolverine Creek.

### 7.6.5 Cumulative Effects

There are no past, existing or foreseeable future activities that would result in effects on groundwater that could overlap with or add to project effects on groundwater. Accordingly there will be not cumulative effects on groundwater in the project area.

### 7.6.6 Mitigation Measures

Table 7.6-8 presents a summary of potential mitigation measures for project effects on groundwater.

### Table 7.6-8 Mitigation Measures for Project Effects on Groundwater

| Potential Project Effect | Mitigation Measures |
|---|---|
| Reduced baseflow in Wolverine Creek resulting in impacts to aquatic habitat during low flow periods | • Based on follow up studies of effects of reduced low flows on fish habitat, evaluate options to reduce groundwater seepage into the mine (i.e., grouting fault zones) |
| Discharge of groundwater contaminants to surface water in Wolverine Creek during closure | • Monitor groundwater quality downgradient of backfilled mine workings during operation. Based on results, initiate enhanced surface water quality monitoring in Wolverine Creek as required. Evaluate contingency measures for enhanced management of groundwater quality at closure |
| **Potential Cumulative Effect** | **Mitigation Measures** |
| None identified. | |

## 7.6.7 Monitoring and Follow-up

### *Follow-up Studies*

No follow-up studies are recommended for groundwater management related to mine dewatering or tailings management.

### *Monitoring Programs*

Monitoring of flow and temperature in Wolverine Creek is recommended during the operation phase to assess effects of mine dewatering on surface water hydrology and aquatic habitat. Monitoring of groundwater quality downgradient of the mine and surface water quality in Wolverine Creek is also recommended during operation and following closure.

Ongoing water level monitoring of mine area piezometers and monitoring wells is recommended to assess the affects mine dewatering is having on groundwater levels and provide advance warning of potential impacts to adjacent surface water systems. As the decline and test mine are advanced and mine development progresses, ongoing review of groundwater seepage into the mine and pumping rates is recommended to refine mine inflow estimates, improve the hydrogeologic model and better assess potential impacts to Wolverine Creek. In addition, it is recommended that the collection of climate data such as precipitation and temperature continue. Monitor water levels in monitoring well MW05-03 located near the portal area (See Section 2.10: Site Facilities and Infrastructure) to determine if gradients change and indicate a reduction in groundwater baseflow to Wolverine Creek.

Table 7.6-9 presents a summary of the proposed monitoring and follow-up programs for groundwater.

### Table 7.6-9 Monitoring and Follow-up Programs for Mine Groundwater

| Potential Project Effect | Program Objectives | General Methods | Reporting | Implemen-tation |
|---|---|---|---|---|
| **Follow-Up Programs** | | | | |
| N/A | • N/A | • N/A | • N/A | N/A |
| **Monitoring Programs** | | | | |
| Reduced baseflow in Wolverine Creek resulting in impacts to aquatic habitat | • Determine if mine dewatering is affecting water quantity and quality in Wolverine Creek | • Year-round (i.e., monthly) monitoring of flow, temperature and water quality in Wolverine Creek | • YTG as required | Proponent |
| | • Provide advance warning of impact to surface water hydrology | • Monitor water levels in mine area piezometers (including MW05-3) and record mine inflow and pumping rates | • YTG as required | Proponent |
| | • Estimate infiltration and predict impacts to surface water hydrology | • Recording of climate data such as precipitation and temperature | • YTG as required | Proponent |
| Discharge of contaminants to surface water in Wolverine Creek watershed | • Determine if water quality is being affected by discharge of mine impacted groundwater following closure | • Monitor groundwater quality in backfilled mine workings during operations and surface water quality in Wolverine Creek | • YTG as required | Proponent |
| **Follow-Up Programs** | | | | |
| N/A | • N/A | • N/A | • N/A | N/A |
| **Monitoring Programs** | | | | |
| N/A | • N/A | • N/A | • N/A | N/A |

**Notes:** N/A = not applicable

## 7.6.8 Summary of Effects

Table 7.6-10 provides a summary of effects related to mine groundwater extraction.

## Table 7.6-10 Summary of Effects Related to Mine Groundwater Extraction

| Potential Effect | Level of Effect[1] | | | | | | Effect Rating[2] | |
|---|---|---|---|---|---|---|---|---|
| | Direc-tion | Magni-tude | Extent | Duration/ Frequency | Reversi-bility | Like-lihood | Project Effect | Cumulative Effect |
| **Construction, Operations and Decommissioning** | | | | | | | | |
| Mine dewatering resulting in groundwater table depression and reduced base flows in Wolverine Creek | Adverse | Low | Local | Long term | Reversible | High | Not significant | N/A |
| **Closure** | | | | | | | | |
| Flooding of mine and gradual recovery of groundwater levels and base flows in Wolverine Creek | Adverse | Low | Local | Long term | Reversible | High | Not significant | N/A |
| Contaminated groundwater from flooded mine discharging to Wolverine Creek and possibly Little Wolverine Lake | Adverse | Low to moderate | Local | Far future | Reversible | Unknown | Not significant | N/A |

**Notes:**
1 Based on criteria in Table 7.6-7
2 Based on criteria in Section 7.6.3
N/A = not applicable