HYDROGEOLOGICAL ASSESSMENT FOR MITIGATION OF GROUNDWATER DISCHARGE TO A CREEK IN A CONFINED VALLEY: PART 1 OF 2 CASE STUDY FROM THE FORMER SULLIVAN MINE, KIMBERLEY, BC

Stefan A. Humphries, M.Sc., P.Geo.

SNC-Lavalin, Inc.
#3-520 Lake Street
Nelson, British Columbia, Canada

Ryan Peterson, M.Sc.
Teck Metals, Ltd.
Bag 2000
Kimberley, British Columbia, Canada

ABSTRACT

The former Sullivan Mine, one of the world's largest producers of lead, zinc and silver, officially closed in 2001 after 92 years of active production. Two large waste rock dumps exist in the incised Mark Creek valley, in what is called the Lower Mine Yard. This area underwent remediation in the 1990s, with an engineered and vegetated cover, isolation of the stream from the rock dump seepage and partial collection of seepage for treatment.

Investigations and monitoring of groundwater and surface water in the Lower Mine Yard have been occurring since the early 1990s. Two aquifers were identified, one a shallow perched aquifer and the second a deep aquifer that is constrained in the valley by a low permeability basal till. Both aquifers have been affected by acid rock drainage and metal leaching from the adjacent waste rock dumps, with vertical groundwater flow from the shallow aquifer affecting the deep aquifer. A hydraulic interception system was installed in the deep aquifer to collect and transmit affected groundwater to Teck's drainage water treatment plant.

In 2012, seepage thought to be from the shallow aquifer was identified in two locations on the south bank of Mark Creek and temporary mitigation measures were implemented to recover affected water. Between 2012 and 2015, intensive investigations took place to understand the cause of the discharges.

The investigations showed that the hydrogeology of the shallow aquifer is complex, and the discharges are related to two different types of perching. The first is a classically perched groundwater unit overlying a lower permeability silt unit, but there no clear mechanism could be identified for the second perched unit. These two types of perching, combined with the interplay of influences from low-elevation snowmelt in March/April and freshet in May/June, required intensive monitoring of groundwater and surface water.

Results from the investigations were used to provide a basis for assessment of remedial options and subsequent design of an interception trench to improve the capture of shallow groundwater in this area and to further mitigate the potential for discharge to Mark Creek.

Key Words: Perched Aquifer, Interception, Trench, Remediation, Acid Rock Drainage.

PREAMBLE

This paper is Part One of a two-part case study. Part Two is titled *Innovative Design and Deep Trench Excavation for a Groundwater Improvement Project*. Readers of this Part One should refer to Part Two for information on remedial options evaluated and, on the remedial option designed and constructed to mitigate groundwater discharge to a creek.

INTRODUCTION

The former Sullivan underground zinc-lead-silver mine is located near Kimberley British Columbia (B.C.), Canada, approximately 500 km east of Vancouver, B.C. The mine operated for 92 years from 1909 to 2001 and was once the world's largest producer of zinc and lead, producing 8 million and 9 million tonnes, respectively. The ore body is considered to be a classic sedimentary-exhalative massive sulphide deposit, with approximately 150 million tonnes of ore produced over its lifetime (Humphries and Peterson, 2011).

The Lower Mine Yard is located in the Mark Creek valley west of Kimberley and south of the Sullivan ore body. The Lower Mine Yard contained the original main entrance to the mine (the 3900' Portal), and mine service areas for much of the operating life of the mine. Two large waste rock dumps exist in the steeply incised Mark Creek valley in the Lower Mine Yard, hereafter referred to as the North and South Waste Rock Dumps.

SITE HISTORY AND BACKGROUND

The Lower Mine Yard was at one time a highly industrialized portion of the Mark Creek valley. Ore was hauled to the Lower Mine Yard for handling until 1947, when the 3700' Portal was developed. Development rock extracted from the 3900' level of the mine and above was placed on the north and south valley walls over the approximate period from 1909 to the mid-1960s. An estimated 4.1 million tonnes of this waste rock was placed over 15 hectares of valley slope.

Reclamation for Closure

As part of closure activities in the 1990s, both the South Waste Rock Dump and North Waste Rock Dump were consolidated, re-graded, and covered with an engineered till cap to reduce infiltration and allow re-vegetation (Gardiner et al., 1997, Przeczek, 2004, Humphries and Peterson, 2011). Photos of the dumps before and after reclamation are shown below.

Figure 1: Before (view looking northwest) and after (view looking southeast) photos of the waste rock dumps adjacent to Mark Creek.

Shallow groundwater seepage from the dumps to Mark Creek was identified to be a concern. In order to isolate the stream from contaminated seepage, a portion of the creek was relocated to a 250 m long concrete flume within the newly consolidated dumps' location, and to a new, rip-rap lined channel located further from the toes of the newly regraded dumps. For the North Waste Rock Dump, a 490 m section of a lined flow-through rock drain and collection point seepage collection system, referred to as the North Trench, was installed within portions of the historical Mark Creek channel (i.e., the historical channel was used for the drain location). The drain and collection point are located up to 20 m from the toe of the current North Waste Rock Dump footprint, and except for a 30 m section at the eastern limit and collection point, was buried below the reclaimed dump surface during re contouring and cover placement. Seepage was directed to the Drainage Water Treatment Plant (DWTP) via pump stations. For the South Waste Rock Dump, shallow seepage was redirected to the deeper aquifer, which was already contaminated, in 1999/2000 by a series of vertical sand drains at the toe of the dump. Hydraulic interception in the deeper aquifer was achieved by an array of pumping wells which intercept water for treatment at the DWTP. A map of the Lower Mine Yard and select features is provided in Figure 2. Discussion of the hydrogeology, groundwater monitoring programs, and mitigation measures provided in sections below.

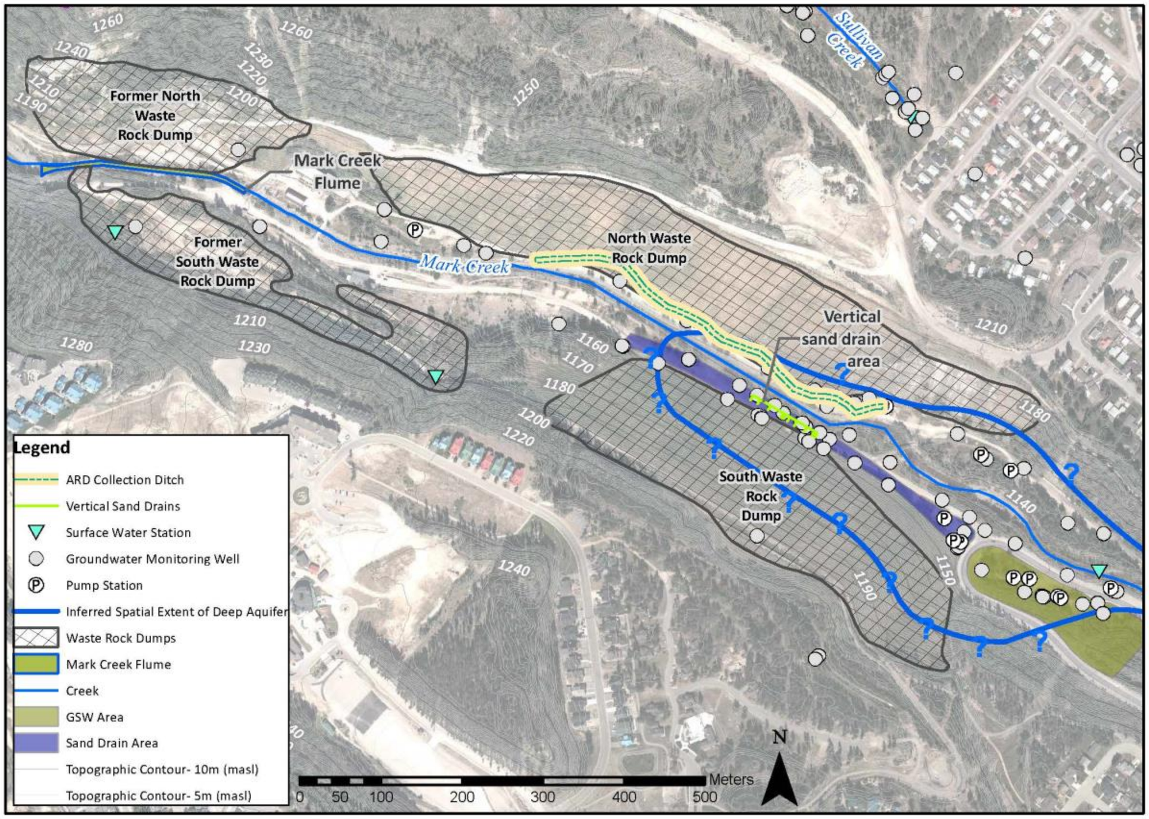

Figure 2: Map of Lower Mine Yard showing former and current waste rock dumps, deep aquifer, and remedial measures implemented in the 1990's and 2000's.

GROUNDWATER INVESTIGATION AND MONITORING

Shallow and deep groundwater investigations have taken place in the Lower Mine Yard since the 1990s. Investigations focused on the geological and hydrogeological controls for the distribution of groundwater affected by Acid Rock Drainage and Metal Leaching (ARD/ML) and the discharge of ARD/ML affected groundwater to Mark Creek. The investigations led to the implementation of the mitigation measures described above to intercept groundwater before discharging to Mark Creek. A Risk Management Plan with monitoring requirements was developed for post-closure monitoring based on the hydrogeological conceptual model; monitoring for the Risk Management Plan included select surface water and groundwater locations in the Lower Mine Yard as well as visual observations of Mark Creek.

GEOLOGY AND HYDROGEOLOGY

The Mark Creek valley in the vicinity of the Lower Mine Yard consists of a steep-sided valley incised approximately 70 m into bedrock. It has been infilled with glacial and fluvial deposits along the valley walls and floor, with bedrock exposure limited to portions of the valley walls towards the west. Post-closure water levels within the Sullivan Mine are maintained below 1,112 m elevation (3650' level), which is below the Lower Mine Yard elevation of about 1,130 m, meaning that bedrock groundwater does not contribute ARD/ML to the Lower Mine Yard.

The base of the incised valley is generally infilled with silt or clay till of up to 17 m thick with overlying sequence of glaciofluvial sand and gravel units interbedded with discontinuous finer-grained sands and silty sands 0.3 m to 5.5 m thick. The finer-grained soils contain silt beds and are thickest and most continuous near the valley centreline, becoming discontinuous near the valley walls. The absence of a thick or continuous confining layer of silt in this area is relevant to the migration of ARD/ML affected groundwater from the shallow aquifer to the deep aquifer, but also shallow groundwater discharge to the creek.

Two main hydrostratigraphic units form the main aquifers beneath the Lower Mine Yard: a thin, perched zone of saturated flood plain sand and gravel (i.e., the shallow aquifer) that is present seasonally in some areas and year-round in others, and; an underlying coarse glaciofluvial sand and gravel valley-fill deposit (i.e., the deep aquifer). Finer-grained soils separating these aquifers mainly along the valley centreline are interpreted to act as a leaky aquitard (i.e., a unit which impedes, but does not prevent, vertical movement of groundwater). Shallow groundwater near the valley centre is perched due to the relative lower vertical permeability of the aquitard that exists between approximately 5 m and 8 m depths. The extent of this aquitard to the east/southeast (i.e., downstream direction) is unknown, but at some point, the shallow and deep aquifers appear to intersect. Figures 3 and 4 below provide conceptual cross sections through the Lower Mine Yard to Mark Creek.

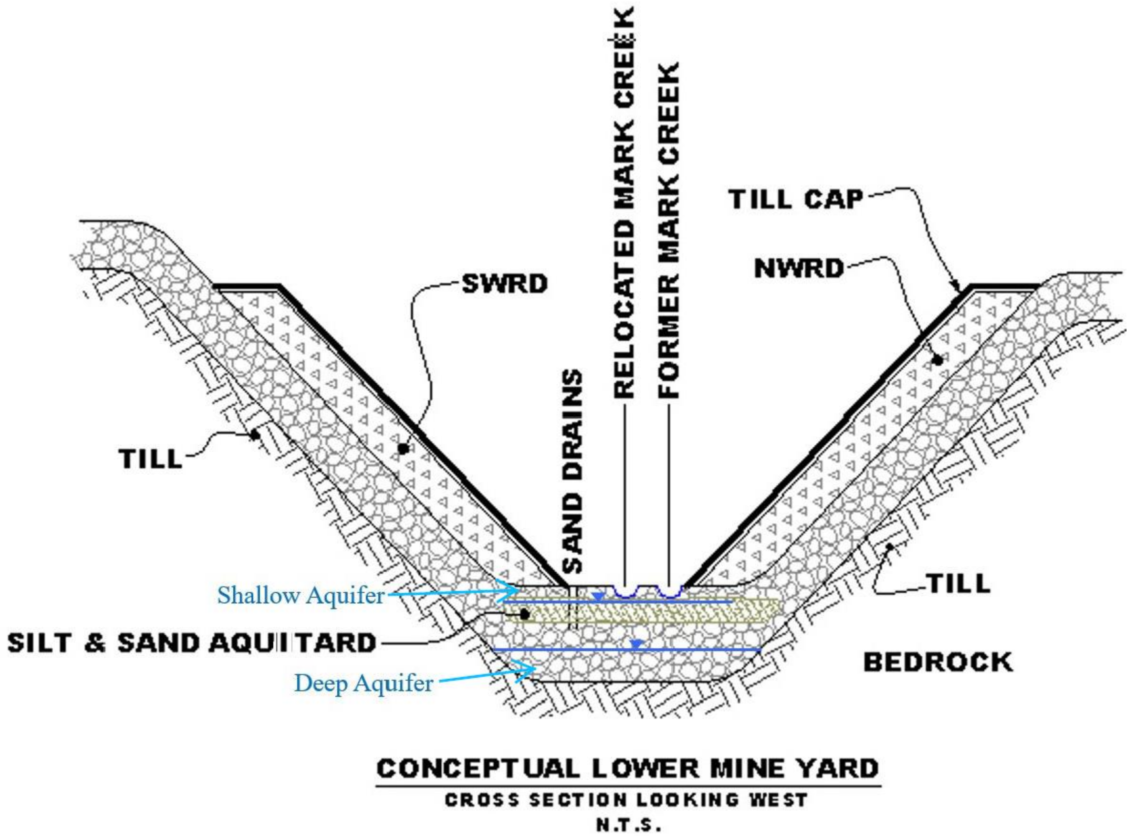

Figure 3: Conceptual cross section showing shallow and deep aquifers – perpendicular to Mark Creek

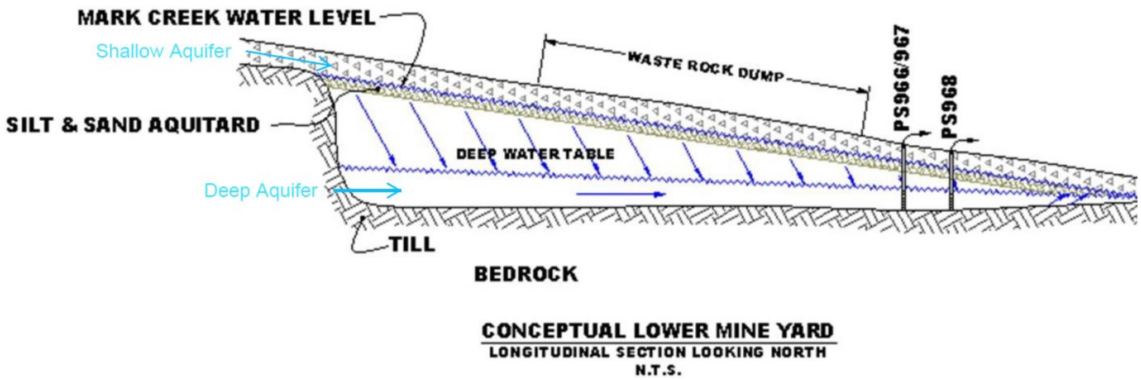

Figure 4: Conceptual cross section showing shallow and deep aquifers and groundwater flow regime – longitudinal to Mark Creek

The natural groundwater flow regime in both shallow and deep aquifers has been altered as a result of past and current mitigation measures. Specifically, the installation of vertical sand drains hydraulically connecting the two aquifers and a number of groundwater pumping wells at various locations have intentionally changed both horizontal and vertical hydraulic gradients and flow directions.

Shallow Perched Aquifer

Horizontal groundwater flow within the perched aquifer is generally towards the centre of the valley and Mark Creek, with some seasonal variations: horizontal flow directions and gradients are highly influenced by the interplay of low elevation melt in April/May; followed by recharge from Mark Creek during freshet in in June. In general, flows occur toward Mark Creek during low elevation snowmelt and more in a down-valley direction during freshet and later months. Additional detail on shallow groundwater flow dynamics is provided in later sections.

Beneath the north bank of Mark Creek at the toe of the North Waste Rock Dump, the bulk of the horizontal flow is intercepted by the former Mark Creek channel and collected with a shallow pumping system installed in the former channel (i.e., the former creek channel functions as a toe drain beneath the North Waste Rock Dump). As noted earlier, beneath the south bank of Mark Creek at the toe of the South Waste Rock Dump, groundwater flow was diverted to the deeper aquifer by installing the vertical sand drains. Overall, the perched nature of the aquifer indicates groundwater seepage from the shallow aquifer would be vertically downwards to the deeper aquifer. The sand drains initially enhanced this condition, by increasing vertical flow and decreasing horizontal flow. However, these sand drains no longer appear to function in this capacity, described later in this paper.

Deep Aquifer

Horizontal groundwater flow in the deep aquifer is generally along the former channel parallel to Mark Creek to the southeast. The deep aquifer is unconfined, with vertical groundwater flow generally downwards from the shallow aquifer to the deep aquifer until a location where the aquifer becomes channeled and pinches out (see Figure 4). At this point, the deep aquifer is semi-confined and upward vertical leakage through the silty aquitard unit naturally leads to discharge of groundwater to Mark Creek. However, the array of pumping wells installed in the deep aquifer to intercept deep groundwater and mitigates discharge to the creek.

GROUNDWATER CHEMISTRY

Groundwater in both the shallow and deep aquifers is affected by ARD/ML. Oxidized sulphide minerals such as pyrrhotite and pyrite in the North Waste Rock Dump and South Waste Rock Dump are the principal sources of ARD/ML within the Lower Mine Yard. Shallow groundwater under these waste rock dumps is generally highly acidic (i.e., pH <3) and contains high concentrations of metals and sulphate. The waste rock dumps were capped with silt till to reduce infiltration and oxygen ingress; however, ARD/ML is still generated due to groundwater seepage from the valley walls and infiltration through the till cover.

Deep groundwater is generally acidic to neutral (historical pH values approximately between 3 and 7), with elevated levels of sulphate, fluoride and a number of different metals. Water quality in the deep aquifer improves along the groundwater flow path, with downgradient wells exhibiting higher pH values and lower sulphate and metals concentrations. This improvement is inferred to result from the presence of the pumping array; however, residual ARD/ML mitigation likely occurs through buffering by dissolution of minerals (e.g., calcite) and cation exchange with the aquifer solids. Since the buffering capacity of the aquifer is finite, an acid front has migrated slowly downgradient over time. In 2002, the acid front reached the groundwater discharge zone during freshet and resulted in contaminant loading and white precipitate within the creek. Teck installed an additional dewatering well to increase the capture of the dewatering system as needed to manage the breakthrough. Subsequent upgrades to the collection system were completed, in part, to provide increased system capacity and flexibility. Teck now operates the groundwater interception system in accordance with the Risk Management Plan and does not rely on formation buffering of ARD/ML as a control measure.

Recent groundwater monitoring as part of the Risk Management Plan (Higgins et. al., 2004, Humphries and Peterson, 2011, Peterson et. al., 2015) suggests that the loading of ARD/ML has increased in pumping wells, adjacent monitoring wells and down-gradient monitoring wells. Groundwater has generally become increasingly acidic at almost all monitoring locations, with the exception of sentinel location 02-10D/15-1. Detailed review and analysis of these data suggest the groundwater ARD plume is both geochemically evolving as well as migrating. Of particular note are recent (i.e., post-2011) elevated results for key indicator parameters at down-gradient locations which suggests reduced capture of the groundwater ARD plume by the hydraulic interception system, likely in combination with depletion of aquifer buffering materials. However, the current groundwater extraction network is considered to be successful at mitigating discharge of acidic groundwater from the deep aquifer to Mark Creek. Additional work to improve capture of the ARD/ML plume in the deep aquifer is ongoing.

SHALLOW GROUNDWATER DISCHARGE EVENTS

More recent (i.e., post 2012) groundwater investigations have largely been focused on the shallow aquifer, related to seepage that was occasionally observed discharging into Mark Creek. In spring 2012, heavy precipitation in Kimberley resulted in elevated groundwater levels following low elevation snow melt. During that time, shallow groundwater with elevated metals concentrations seeped into Mark Creek in three locations: one on the north side of the creek, related to a blockage in the North Waste Rock Dump toe drain (i.e., the former Mark Creek channel); one on the south side of Mark Creek proximate to the sand drains; and, one further downstream on the south side along Gerry Sorensen Way. In 2014, additional seepage was discovered in a side channel downstream of the sand drain area. Figure 5 below shows approximate areas where discharge to Mark Creek occurred from shallow groundwater.

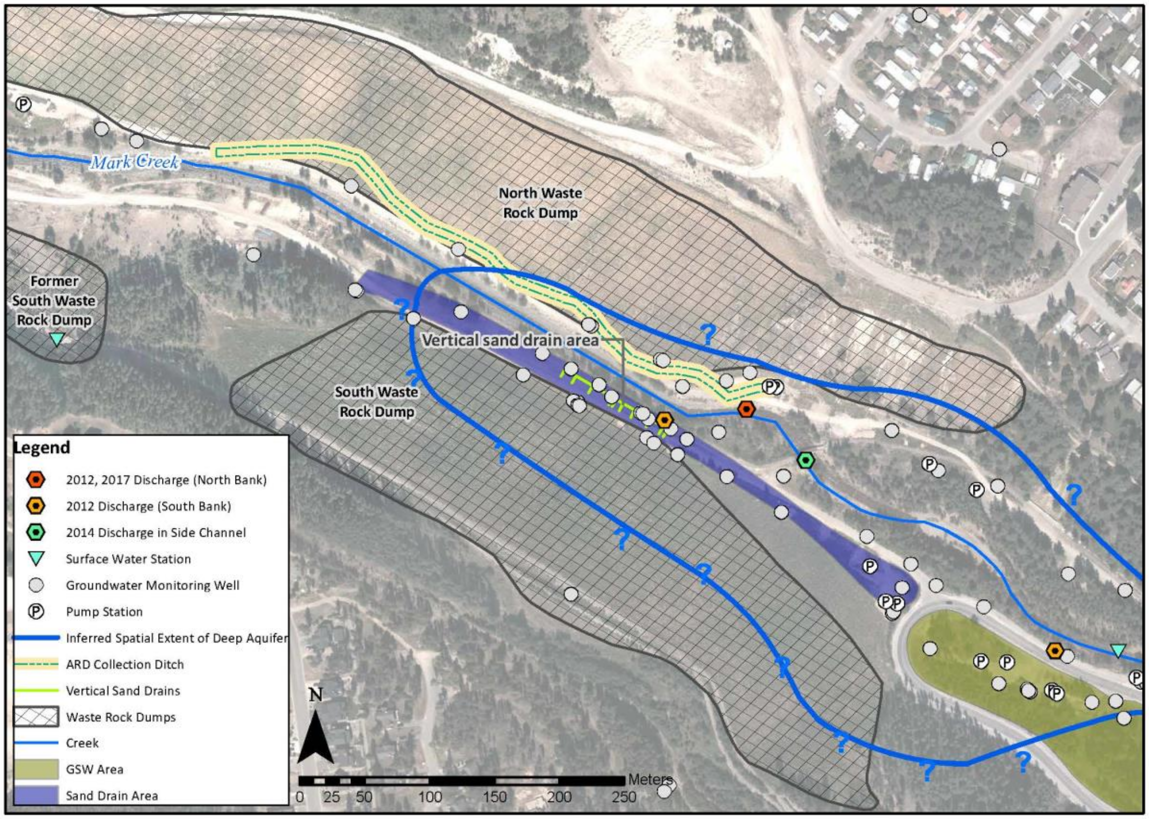

Figure 5: Approximate areas of groundwater discharge from the shallow aquifer

SUPPLEMENTAL SHALLOW GROUNDWATER CHARACTERIZATION AND REMEDIATION

A number of supplemental investigations took place to understand the hydraulic properties, extent and groundwater flow regime of the shallow aquifer, briefly described below. Shallow, perched groundwater (seasonal in some areas) was identified as the source of the seepage. The nature and extent of the perched groundwater depends on the differences in hydraulic properties between the upper sand and gravel unit and underlying units.

Temporary remedial measures in the form of pumping wells and pump stations installed in small interception trenches were installed immediately after the discharges were identified, but it was recognized that a long-term remedial solution was required. Teck undertook a comprehensive remedial options analysis and selected the remedial option of a groundwater interception trench system. Details on the remedial options analysis and interception trench are provided in the accompanying paper submitted as Part 2 of 2 of this case study.

Shallow Groundwater under South Waste Rock Dump

The investigations showed that the hydrogeology of the shallow aquifer under the South Waste Rock Dump is complex, and the discharges to Mark Creek were related to two different types of perching. As a result, shallow groundwater under the south waste rock dump was characterized into two areas:

- Sand Drain Area (i.e., in the vicinity of the vertical sand drains): The discharge events indicated that the vertical sand drains were no longer functioning adequately, resulting in preferential horizontal flow to Mark Creek over vertical flow to the deep aquifer. There is no clear aquitard unit in this area that results in the perching; the stratigraphy consists of two sand and gravel units, the upper comprising trace (i.e., 0-10%) silt and the lower unit comprising some (i.e., 10-20%) silt. Shallow groundwater is perched at the general interface between these two units and perching is inferred to result from the slightly higher proportion of finer-grained materials. With the exception of periods during low elevation snowmelt (i.e., March/April), groundwater elevations are similar to Mark Creek water levels and they mimic seasonal fluctuations in the creek, suggesting a direct hydraulic connection to the creek. During the majority of the year, downward seepage occurs to a deeper aquifer; however, seepage to the creek as horizontal groundwater flow can occur following low elevation snow melt. Seepage has generally been observed before or after high water events in Mark Creek (i.e., freshet during May/June).

- Gerry Sorensen Way Area: The aquitard in this area consists of a low-permeability silt unit that results in a classically perched groundwater unit and more defined, but seasonal, perched groundwater at elevations higher than Mark Creek. These units are relatively continuous; however, there are some localized areas where no silt is present. Wells installed in the shallow perched unit are generally dry until recharge from low elevation snow melt. The subsurface topography of the silt/upper till governs groundwater flow regime and seepage of ARD/ML-affected groundwater to the creek.

The understanding of these two different hydrogeologic regimes was used in the design basis for the construction of a groundwater interception trench system that spanned both areas. The spanning of both areas presented a challenge; specifically, the depth to the base of the interception trench had to be governed by the horizontal flow in the non-classically perched shallow aquifer in the Sand Drain Area. A detailed understanding of water levels, hydraulic gradients, hydraulic conductivities and seasonality of the shallow groundwater was required.

<u>Shallow Groundwater under North Waste Rock Dump</u>

Similar to the shallow aquifer under the South Waste Rock Dump in the Sand Drain Area, groundwater is perched within a sand and gravel unit that has a higher silt content. Shallow groundwater flows in the down-valley direction, not towards the adjacent Mark Creek, which suggests groundwater recharge from infiltration of Mark Creek. During May to September, flow is parallel to the creek until an area where the creek takes a slight bend, resulting in groundwater discharge, concurrent with where the seepage was observed in April 2012 and again in April 2017. During the remainder of the year, groundwater flow is away from the creek. A number of factors contributed to the discharge to Mark Creek, including: plugging of the existing ARD collection system upgradient of the discharge area; increased loading during low-elevation snow melt; and, the presence of an inferred preferential groundwater pathway along the former Mark Creek channel. Groundwater and surface water data from along the toe of the North Waste Rock Dump to the northwest of the breakthrough area suggest the remainder of the North Trench is capturing ARD in this area. Part 2 of 2 of this case study presents the design for upgrades completed to mitigate bypass of the North Trench near the central collection point.

SUMMARY AND CONCLUSIONS

ARD/ML has affected both shallow and deep aquifers near the South Waste Rock Dump and North Waste Rock Dump and a number of remedial measures were undertaken in the late 1990s and early 2000s. More recently, episodic groundwater discharge events occurred from the shallow aquifer to Mark Creek. Temporary measures to intercept the groundwater were implemented while investigations and remedial options analyses took place.

One of the main conclusions from the recent investigations was that that there were two different types of perched conditions in the shallow aquifer. The characterization of these conditions required a number of groundwater monitoring wells and implementing a comprehensive monitoring program for groundwater and surface water. This is because the complexity of the groundwater flow regime and the controls on it varied by season and therefore intensive monitoring was required. Ultimately, the high degree of characterization was important for the design and construction of the two groundwater interception trenches.

REFERENCES

Gardiner, R.T., Dawson, B.B., Gibson, G.G., Application of ARD abatement technology in reclamation of tailings ponds at Cominco Ltd., In: Proceedings of 4th International Conference on Acid Rock Drainage, Vancouver, BC, Canada, June, 1997

Higgins, C., Wilson, R., Sandstrom, N., Dawson, B., Mann, G., Allard, P. and Baker, R. (2004) Post Closure Human Health and Ecological Risk Assessment at Teck Cominco’s Kimberley Operations, BC Overview of Regulatory Process and Findings of the Problem Formulation, Proceedings from 2004 Technical and Research Committee on Reclamation (TRCR) Annual Mine Reclamation Symposium, June 23, Cranbrook, BC, Canada.

Peterson, R. A., Humphries, S. A., Unger, M. L. Adaptive risk management and lessons learned: post-closure at the "mighty" Sullivan mine. 2015 BC TRCR and Mine Closure Conference, Vancouver, BC, Canada.

Humphries, S. A., and Peterson, R. A. Long-term post-closure surface water and groundwater risk management and subsequent water quality trends at the former Sullivan Mine, Kimberley, BC, Canada. 2011 BC TRCR and Mine Closure Conference, Lake Louise, AB

Przeczek, J. (2004) Review of the Reclamation Research Program at Teck Cominco’s Sullivan Mine at Kimberley, BC, Proceedings from 2004 TRCR Annual Mine Reclamation Symposium, June 23, Cranbrook, BC, Canada.