Underground Mine Surface Water Inflow Hazard Assessment

Robert McLean
Artifex Engineering Hydrology - mine hydro consulting, Victoria, British Columbia, Canada

ABSTRACT
There are several forms of hazard when considering water inflow to an underground mine. This paper discusses assessment methods of the geologic hazard that is created by infiltration of surface water and restricted drainage within unconsolidated mine backfill material. High pore water pressure within the unconsolidated backfill along with ground water pressures within the mine development could potentially lead to the movement of the material. Analysis of the issue at an operating underground mine is discussed using a mine water balance, mine water discharge recession after a large precipitation input, and a base flow index. Proposed methods are discussed for the assessment of the issue, using localized flow and ground water pressure data, as well as natural isotope and artificial tracer studies. Prior to conducting a tracer study, considerable effort is required to characterize the complex hydrologic system of an operating underground mine. This paper will provide a useful reference for mine technical personnel or hydrology professionals not familiar with mine operations who are tasked with conducting a similar analysis.

RÉSUMÉ
Il existe plusieurs formes de danger lors de l'examen d’arrivée d'eau dans une mine souterraine. Cet article décrit les méthodes d’évaluation de l'aléa géologique créé par l'infiltration des eaux de surface et le drainage limité dans les matériaux de remblais non consolidés. Les hautes pressions d'eau dans le remblai non consolidée ainsi que les pressions d'eau souterraine dans le développement de la mine pourrait entraîner des mouvements des matériaux. L’analyse de la question dans une mine souterraine d'exploitation est présenté à l'aide d'une balance de la mine de l'eau, la mine récession d'évacuation d'eau après une grande entrée de précipitations, et un indice de débit de base. Les méthodes proposées sont examinées pour l'évaluation de la question, en utilisant un écoulement localisé et les données de pression de l'eau du sol, ainsi que des études isotopiques naturel et traceurs artificiels. Avant de procéder à une étude de suivi, des efforts considérables sont nécessaires pour caractériser le système hydrologique complexe d'une mine souterraine d'exploitation. Ce document constituera une référence utile pour le personnel technique des mines ou des professionnels de l'hydrologie n’éant pas familiers avec les opérations minières qui sont chargés de procéder à une analyse similaire.

1 INTRODUCTION

This paper addresses the issue of surface water entering underground mine workings resulting in the increase of unconsolidated backfill pore water pressure and the resulting potential movement of the material. The inflow quantity addressed was not considered to be the magnitude of an inundation flow such as the redirection of a flooding river into the mine workings. Rather, the flows would be generated by snowmelt or rainfall events from a limited catchment area. A case study is discussed for an assessment that was completed at the Kidd Operations mine. The mine started as an open pit in 1966 and once the surface operation was complete, production moved underground. Due to the age of the mine, there are many areas that are inactive and no longer accessible. There is a potential for geologic material particles to have been transported with ground water flow, or materials removed from the mine sump water, and deposited in areas that would cause a restriction to flow. Kidd Operations is the deepest base metal mine in the world and is approximately 2900 m deep. The depth of the mine results in high working temperatures and therefore cooling requirements to provide a suitable working environment for employees. Operations may continue for several more years dependent on commodity prices and operational costs.

The goal of the project at the case study mine, was to assess if it could be determined, with available data, if water was being stored in inactive and inaccessible mine workings (and surrounding fractured rock) or if the system was freely draining. Options for further investigation were also to be provided. The buildup of water pressure and the movement of material is a concern in all operating mines and is not exclusive to the case study. An analysis of the spatial extent of the mine developments, the locations and volume of backfill material, the locations of mine development bulkheads and rock geotechnical information were all beyond the scope of the assessment.

1.1 Definition of the Backfill Stability Issue at Mines

Backfilling of mine developments with material such as waste rock, tailings, or mine water sediment has historically been completed as a disposal method. Some mines have large quantities of surface water inflows that may transport and deposit geologic material particles within the mine. Some pits have been backfilled with materials that provide a source of particles. These sediments can act to restrict flow through fractured rock and/or fill mine developments. Figure 1 shows a schematic of a mine development that was backfilled with unconsolidated material and is subject to water entering, leaving and being stored within the development, potentially raising pore water pressures within the backfill material to such levels that the material could begin to flow.

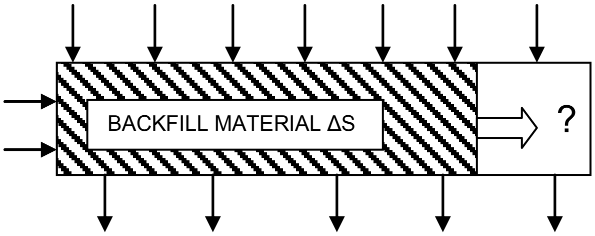

Figure 1. Schematic of mine development backfilled with unconsolidated material and subject to surface water inflow, outflow and change in storage (ΔS)

Hypothetical ground water and backfill material seasonal pressure fluctuations caused by spring snowmelt and summer rainstorms for a backfilled mine development exposed to surface water inflow in the Northern Hemisphere is shown in Figure 2. During the winter months, when there is no input to the hydrologic system, the pore water pressures are likely stable or slowly decreasing. Figure 2 is fictional and for example purposes only. The actual yearly pore water or ground water pressures observe in unconsolidated material mine backfill will depend on the volume and timing of the water inflow, permeability and storage characteristics of the rock surrounding the development as well as the backfill material.

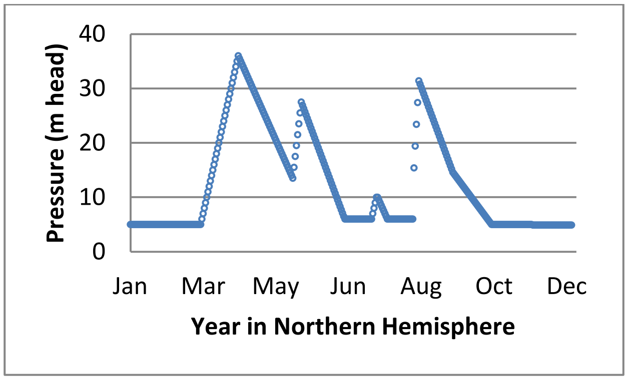

Figure 2. Schematic of likely ground water and backfill material seasonal pressure within backfilled mine developments. Note the data is fictional and for example purposes only.

1.2 Hydrologic System of the Case Study Mine

The hydrologic system of the case study mine consists of a mined out open pit underlain by several levels of extensive underground mine workings in a hard rock environment. Much of the inactive upper layers of the underground workings were backfilled with waste rock, mine water sediment and engineered paste fill. Much of the upper level developments are no longer accessible for geotechnical safety reasons. Active mine developments are located below the inactive mine workings. The ore body is accessed using ramps and shafts along with a cork-screw type incline. As much diversion of surface flows away from the pit as practical is conducted to minimize inflow to the mine. Dewatering from the base of the pit is not practical due to the high permeability of the base as well as pit wall instability. Figure 3 presents a plan view drawing of the case study pit outline, upper level underground mine developments, and exploration drillholes advanced into the surrounding rock from within the mine. Depending on the permeability of the rock surrounding the mine developments, permeability of the backfill materials, and drainage system within the mine, water will percolate downward and be intercepted by the mine dewatering system at different levels. Note only a few of the drillholes are shown for information purposes. Operating underground mines typically have an extensive network of drillholes advanced ahead of production. These boreholes may be open and available for a ground water study or grouted shut if mine protocol requires it.

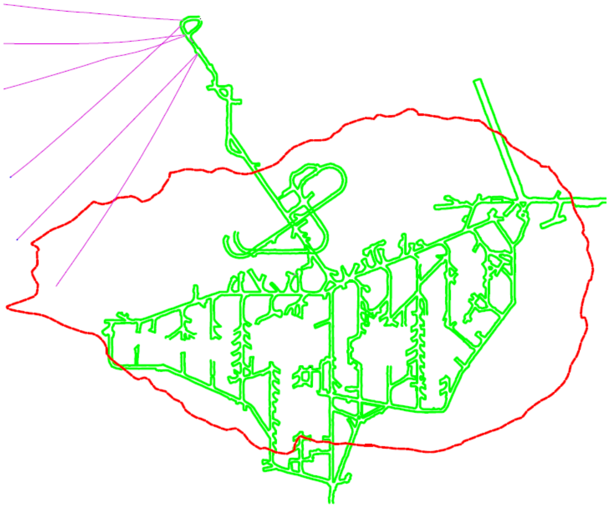

Figure 3. Plan view drawing of pit outline showing some underground mine developments and drillholes at the case study mine

Sumps are located within the underground mine every 122 m depth. Water enters the mine developments via the open pit from snowmelt and rainfall events. The mine has an ongoing program to ensure drainage systems are functioning. An extensive network of drillholes, above and beyond the mine developments, provide drainage of the surrounding fractured rock. Due to the size and age of the mine as well as the inaccessibility of some of the inactive developments, there however remains a potential for water to be stored behind unconsolidated materials posing a hazard to localized mine operations.

The case study mine is a relatively dry mine based on the daily mine water discharge and the extent of the mine workings. The mine is the deepest base metal mine in the world and geothermal energy from the lower active mine developments is a source of heat that could cause melting of snow in the pit on days when the air temperature is less than 0°C. During the winter, cold air is drawn into the mine through the upper mine levels causing ice to form in the developments. During the summer, air is drawn into the mine through these frozen developments to lower the working environment temperature for employees. This melting of the ice in the developments is a source of inflow to the mine and may add to the "noise" in the mine water discharge data.

2 ASSESSMENT USING A MINE WATER BALANCE

Initial assessment of the hydrologic system with the available data consisted of conducting a water balance of the operating underground case study mine. Golder (2011) provides a useful reference for conducting a mine water balance. An assessment was conducted to determine if water was being stored in the mine developments and to better understand the hydrologic system of the mine by evaluation of equation 1 on an annual basis.

$$\sum \text{Inflow} - \sum \text{Outflow} = \Delta \text{Storage} \quad [1]$$

Water inputs to the mine include:

- precipitation (rain and snow) through the pit,
- shallow ground water from local natural water bodies and site water management facilities,
- deep ground water,
- atmospheric water that is injected by the mine ventilation system,
- melting ice from the upper level developments,
- process water as required for the mine operations (drilling, dust control, etc.), and
- backfill material water and equipment flush water that escapes from the paste and waste rock fill.

Water outputs from the mine include:

- mine water discharge,
- ventilation water lost from the mine workings through evaporation, and
- water contained in the ore.

Some of the above parameters were measured, some could be approximately calculated and some were estimated. Five years of mine water discharge data from 2008 through May 2013 was available.

The annual volume of precipitation entering the mine developments was determined through onsite snow depth measurements and daily rainfall records from a regional meteorological station. The annual volume ranged from 245,000 to 514,000 m^3/year. The actual depth of snow in the pit may be much different than measured at surface and there was no available data to assess the correlation of site rainfall with the regional meteorological station. The catchment area of the pit was estimated using engineering drawings and site personnel knowledge of the local drainage.

Inflows from shallow sources were small and deep ground water sources were negligible based on site personnel knowledge. Using the annual water balance it was estimated the annual ground water inflow from shallow, deep and melting ice in the upper development sources was approximately 180,000 m^3/year.

The water injected to and removed from the mine developments, by the ventilation system, was estimated using methods presented in Younger et al. (2002) and Raven and Gale (1986). The ventilation system water input was calculated to range from 160,000 to 190,000 m^3/year and the loss of water from the mine due to the ventilation system was estimated to be 800,000 m^3/year including water droplets. The published methods for estimating ventilation air gains and losses determined water only in the gaseous form. Some water is also exhausted from the high velocity ventilation system in droplets.

Process water entering the mine was estimated (based on total flow rates from a site reservoir) to range from 33,000 to 540,000 m^3/year. Years of low precipitation required higher process water inputs. A mine water circulation system is used to provide process water within the mine and an automatic system provides water from surface as required.

Mine water discharge was measured to range from 62,000 to 330,000 m^3/year and water removed with the ore was estimated to range from 30,000 to 40,000 m^3/year.

Calculation of an annual water balance over a five year period, using a consistent method, resulted in no trend of increasing apparent storage within the mine. The water balance was determined to be a worthwhile exercise to better understand the magnitude of inflows and outflows to the hydrologic system. However, no firm conclusions regarding storage of water within the mine developments could be drawn from the data.

3 ASSESSMENT USING MINE WATER DISCHARGE

Assessment of the hydrologic system with the available data also consisted of an evaluation of the mine water discharge recession characteristics, after a precipitation event, and base flow index on an annual basis.

3.1 Mine Water Discharge Recession

Stream flow recession, in the field of surface water hydrology, is a well researched and documented area of hydrological engineering. Stream flow recession is controlled by several factors including rock storage and hydraulic conductivity characteristics as well as surface storage in lakes, wetlands, and manmade reservoirs. The situation of surface water entering the subsurface, through many pathways, and ultimately entering the underground workings is analogous to a surface stream that has both base flow as well as storm flow (runoff) components. There are several available techniques to separate a hydrograph's base flow and runoff components as well as characterize the storage and transmissivity properties of the medium the water has flowed through. Walton-Day and Poeter (2009) used a method provided in Watson and Burnett (1995) to estimate base flow recession constants and curves to characterize flow from a mine tunnel and thereby draw conclusions on the hydrologic effect of a rock collapse that occurred in the Dinero mine tunnel in Colorado.

Upon review, the mine water discharge data contains several components that create noise and appear impossible to remove without the collection of further data and the refinement of calculations. These include gains/losses from the ventilation system, mine operations water input, and backfill material water input.

The mine water discharge and precipitation data was reviewed for the available mine water discharge data from January 2008 to May 2013 to identify large precipitation events followed by a minimum of 15 days of no precipitation. Only six mine water discharge recession periods were chosen that fit the criteria. Four of these events were spring snow melts and therefore subject to freeze and thaw cycles which affects the daily discharge values. Local meteorological characteristics appear to contain very few large intensity rain storms that are followed by several weeks of precipitation free days. A large precipitation event followed by an extended period of dry weather would be preferable for recession analysis. These recessions are plotted with absolute values in Figure 4 and normalized discharge in Figure 5. Both figures show it is difficult to draw conclusions with respect to annual changes of storage within the hydrologic system. However, the figures do provide some insight into how large precipitation events move through the mine's hydrologic system.

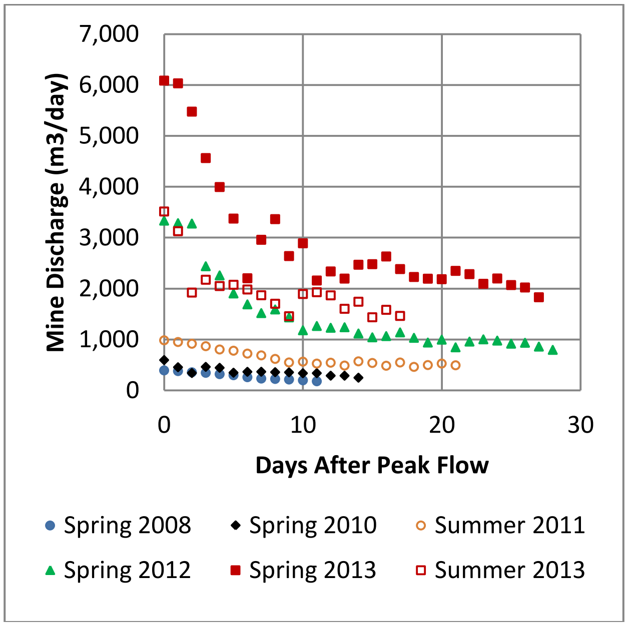

Figure 4. Selected mine water discharge recession events

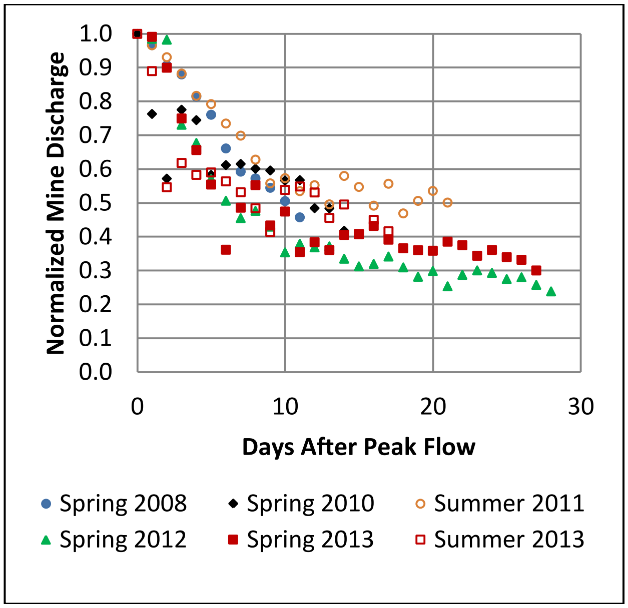

Figure 5. Normalized mine water discharge recession events

3.2 Mine Water Discharge Base Flow Index

Base flow index (BFI) was developed by the Institute of Hydrology (1980) and can be thought of as the proportion of the annual runoff that derives from stored sources. The more permeable the materials (soil, unconsolidated deposits and rock) the base flow travels through, the more constant the base flow and the more sustained the river's flow during periods of no precipitation. The BFI is defined as the ratio of the total yearly base flow to the total yearly flow and is calculated by using daily stream flow data. The procedure consists of calculating the 5-day minimum flow (N value), looking for the turning points in the sequence of minimum flow plotted against time, and connecting the turning points to create a base flow hydrograph. The area under this base flow hydrograph is divided by the area under the total hydrograph to calculate the BFI.

The BFI may be thought of as a measure of the proportion of the river runoff that derives from stored sources and is therefore an effective means of indexing catchment geology as discussed in the Institute of Hydrology (1980). In general, rivers draining low permeability clay catchments have low (less than 0.4) values of BFI whereas catchments consisting of near surface fractured rock and gravels have higher (greater than 0.5) values of BFI as discussed in McLean and Watt (2005). The BFI is also however dependent on the annual total precipitation as well as the consistency of rainfall received in a catchment. McLean and Watt (2005) reported a median BFI standard deviation of 0.07 for 38 catchments located northwest of Toronto within an approximately homogeneous precipitation region. The years of available stream flow data used to calculate the BFI values varied from 9 to 50 years.

For the case study, mine water discharge BFI was calculated using software developed by Wahl (2001), at the U.S. Department of the Interior Bureau of

Reclamation. The Wahl (2001) software allows calculation of BFI using any value of N.

The 2012 mine water daily discharge and Institute of Hydrology (1980) base flow discharge is presented in Figure 6. Note the spring melt discharge in March and the frequent increases in discharge that occurred throughout the year, even during the winter when it would be expected the mine water discharge would be relatively constant. As discussed in Section 1.2, the case study mine provides considerable geothermal energy that may melt pit snow on days when the air temperature is less than 0°C. This "noise" in the data caused by melting snow and by mine operations activity would be difficult to remove from the data at most operating mines.

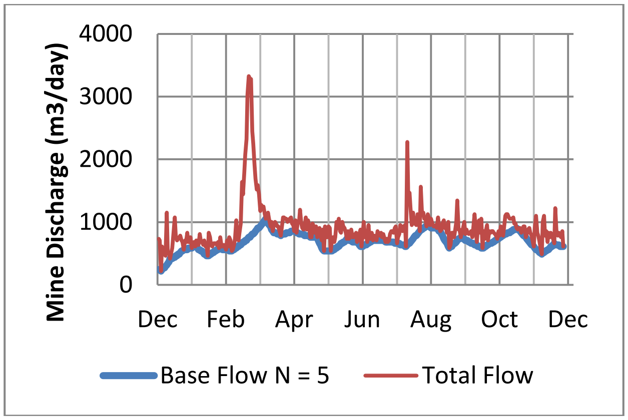

Figure 6. Measured daily mine water discharge and base flow for 2012

The mine water discharge BFI was calculated for each year by the ratio of the total years base flow discharge to the total discharge. As discussed in Section 2, the daily mine water discharge is influenced by several mine water balance parameters. The goal of the study was to assess the drainage characteristics of the upper mine and surrounding rock, given precipitation inputs through the open pit. The mine water total and base flow discharges were adjusted by subtracting the annual ventilation input, subtracting the annual process water input, adding the annual ventilation system loss and adding annual ore loss.

Table 1 presents the results of the annual values of BFI determined using the Wahl (2001) software along with the annual calculated volume of water that entered the pit between 2008 and 2012.

Table 1. Annual volume of precipitation entering pit and mine discharge BFI values (N=5)

Year	Precipitation Volume (m^3)	BFI
2008	514,000	0.98
2009	447,000	0.87
2010	228,000	0.88
2011	286,000	0.85
2012	245,000	0.81

The relation between annual volume of precipitation entering the pit and BFI of the case study annual mine water discharge is shown in Figure 7. As the figure shows, there is a general increase in calculated BFI values for increases in annual precipitation. There are several other factors at play that affect the correlation between these variables. In addition, the consistency of rainfall events throughout the year will affect the value of BFI.

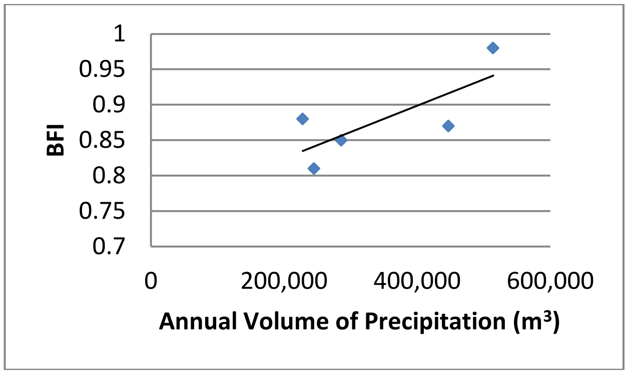

Figure 7. Relation between annual volume of precipitation entering the pit and BFI of case study annual mine water discharge

4 ASSESSMENT WITH LOCAL FLOWS

Discussion of this section is with respect to all operating mines. Sections 2 and 3 discussed assessment of the total mine hydrologic system. Continuous measurement of localized flows from inactive mine developments and drillholes at operating mines would provide useful data for the assessment of drainage characteristics in these areas.

4.1 Individual Development Water Discharge

Measurement of discharge from individual inactive mine developments may provide useable information to identify areas that are temporarily storing water. The inactive mine developments should be subject to no other hydrologic inputs other than the steady state ground water inflow and the periodic infiltration of precipitation. That is, there should be no operational inflows from drills and the ventilation system for the areas should be shut down. Development areas that do not drain quickly after a large precipitation event could be targeted for a drilling program to install ground water pressure monitoring equipment or to use the drillholes as drains. Alternatively, bulkheads could be constructed in these areas to mitigate any potential backfill material movements if there was sufficient information to justify the expenditure. The available flow data will vary considerably at all mines.

4.2 Drillhole Flow Discharge

Continuous measurement of flow from drillholes completed laterally outward from the mine (as shown in Figure 3) may provide useful information to identify areas that are slow to drain in operating mines. Long term data would be required for such an analysis.

4.3 Drillhole Water Pressure

Continuous measurement of ground water pressures in rock surrounding inactive developments would provide information to assess how local pressures change after a large precipitation event. As discussed above, most operating underground mines have an extensive number of exploration drillholes completed in the rock surrounding the mine developments. Depending on mine operational protocols, most or all drillholes may however be grouted. Capping of available drillholes and installation of pressure data loggers would provide such data. At many operating mines, these drillholes may be several hundred meters long. However, even pressure data from such long drillholes is useful but should be interpreted with care using core fracture and grout records.

4.4 Water Quality Measurements

Water quality measurements of flow from inactive mine developments and available drillholes would provide useful information to assess the local hydrologic system. Field measureable parameters temperature, electrical conductivity and turbidity could be measured regularly to determine background values. In particular, measurement of these parameters during winter months in environments that are freezing would allow a baseline evaluation with no precipitation inputs. Regular measurement of these parameters after a large precipitation event may help to identify areas that are slow draining. In addition, periodic sample collection for laboratory analyses of major ions and trace metals may also provide useful data to evaluate areas that drain slowly after a large precipitation event.

5 ASSESSMENT WITH TRACER STUDIES

A review of tracer studies was conducted to determine if this approach would be suitable to study the issue under discussion in this paper. Both environmental (natural) tracers and artificial tracers were considered. Environmental tracers include stable isotopes, anthropogenic chemicals that have accidentally entered the hydrologic system, organisms and physical influences such as water temperature as discussed in Wolkersdorfer (2008). Water-soluble tracers include dyes, salts, and radioactive and neutron activatible tracers. Water-insoluble tracers including solid particles, viruses, bacteria, microspheres and spores.

Isotopes of hydrogen and oxygen have been previously used with chemical and physical hydrologic data to interpret sources of inflow to a mine in studies by Hazen et al. (2002), Walton-Day and Poeter (2009), and by the author for the unpublished study of inflows to an underground mine in the Northwest Territories and the baseline hydrogeology assessment for an underground mine on Vancouver Island. There are many other types of isotopes that could be analyzed in water samples to interpret the source of water entering a mine. For brevity, only hydrogen and oxygen are discussed in this paper as they appear to be the most common isotopes utilized for hydrogeology studies. In addition, laboratory costs for the analysis of these isotopes is very reasonable.

The following types of questions could potentially be addressed with a tracer study at a mine such as the case study site. What are the main sources of steady state ground water entering different locations throughout the mine? What is the lateral and vertical extent, within the mine, of precipitation water that has entered through the open pit after a large precipitation event? How many days does it take for a large input of water to travel through the fractured rock, mine developments, and backfill materials?

There are obvious advantages and disadvantages to both approaches. Environmental tracers are free and are everywhere in the hydrologic cycle. However, as discussed, the input signature cannot be controlled. Most artificial tracers must be purchased, transported to site, and injected into the hydrologic system at the correct location and approximately correct mass to meet the physical requirements of the system under study. Environmental tracers must be collected in water samples and submitted to a qualified laboratory for analysis. Some artificial tracer concentrations may be measured in the field with handheld sensors.

There are however many issues with respect to the hydrologic system of a mine that must be addressed prior to conducting a tracer study. As discussed with the case study mine in Section 2, large volumes of water are potentially lost and added to an underground mine through the ventilation system. It must be clearly understood if the area where a tracer study is proposed could be affected by the ventilation system and if so sufficient data collected to interpret the results of such a study.

Once the objectives of a study have been identified, mine water balance information assembled, mine water pumping system documented, potential sample locations identified, hydrogeology of the area characterized, and localized flow, pressure and chemical data has been collected, a hydrologist experienced with tracer studies should be consulted to provide input to the planning of a field program as well as with interpretation of the data.

5.1 Natural Isotope Tracers

Natural tracer studies using hydrogen and oxygen isotopes are a well documented methodology of assessing ground water flow systems related to mine hydrology. Clark and Fritz (1997) provide a reader with a theoretical and practical background of the use of environmental isotopes in hydrogeology and is a common reference for mine hydrogeology studies. The naturally occurring stable isotopes oxygen-18 (^{18}O) and hydrogen or deuterium (^{2}H) are ideal natural tracers and are commonly used in mine hydrogeology studies.

The input of natural isotope tracers of hydrogen and oxygen to a hydrologic system consists of rainfall or snowmelt. The natural isotope signature is controlled by environmental physical laws and cannot be changed by the researcher. For example, the isotope signature of a rainstorm may vary over time as the storm progresses and the signature of snow will change as sublimation occurs. Fritz et al. (1975) provide a discussion of rainfall sampling for oxygen and hydrogen isotopes at four locations in Canada and snow sampling procedures for isotope analysis are provided in Ingersoll *et al.* (2002). Clark and Fritz (1997) also contains a dedicated chapter discussing that the isotope signature of hydrogen and oxygen in precipitation is controlled by temperature. These include the global effects of latitude and the continents as wells as local effects of altitude and seasons. Stable isotopes exhibit systematic variations within the hydrologic cycle due to fractionation effects caused by phase changes and diffusive processes (Stadnyk *et al.*, 2005). As a result, stable isotopes can be used to predict the source and possibly the flow path the sample has taken.

Isotopes of deuterium and ^{18}O are very good water tracers as they are naturally occurring in water molecules, behave conservatively (are relatively non-reactive) and have different "signatures" as discussed in Stadnyk *et al.* (2005). In addition, they are stable or do not spontaneously disintegrate by some form of known decay compared with an unstable or radioactive nuclide (Clark and Fritz, 1997). The residence time of water in different environments with varying temperature, humidity, and other environmental conditions that control evaporation results in a characteristic signature of the water as discussed in Clark and Fritz (1997). This makes the use of these naturally occurring stable isotopes suitable for characterizing the origin of water entering the mine.

Most oxygen has a nuclide with an atomic mass of 16 units or ^{16}O. Similarly, most hydrogen has a nuclide with an atomic mass of ^{1}H. Stable isotope ratios ^{18}O/^{16}O and ^{2}H/^{1}H are commonly expressed as δ^{18}O and δ^{2}H values relative to Vienna Standard Mean Ocean Water (VSMOW) as discussed in Clarke and Fritz (1997). The units of δ^{18}O and δ^{2}H are parts per thousand or permil (‰) difference from the reference (Clark and Fritz, 1997). Clark and Fritz (1997) and Walton-Day and Poeter (2009) provide explanations of how the values of δ^{18}O and δ^{2}H are determined by a laboratory. The overall isotopic composition of a samples δ^{18}O and δ^{2}H values are commonly shown visually as a plot in δ^{18}O and δ^{2}H space.

Figure 8 is presented as an example of how δ^{18}O (18O in the figure) and δ^{2}H (2H) data can be used for a hydrogeological assessment. The figure shows the sample data is divided into three separate groups consisting of deep ground water (Group 1), shallow ground water connected to the annual hydrologic cycle (Group 2) consisting of creek and shallow unconsolidated material ground water samples and one high intensity precipitation sample (the red triangle). The line through the plot is the Global Meteoric Water Line (GMWL), a reference for interpreting the origin of ground water data as discussed in Clark and Fritz (1997).

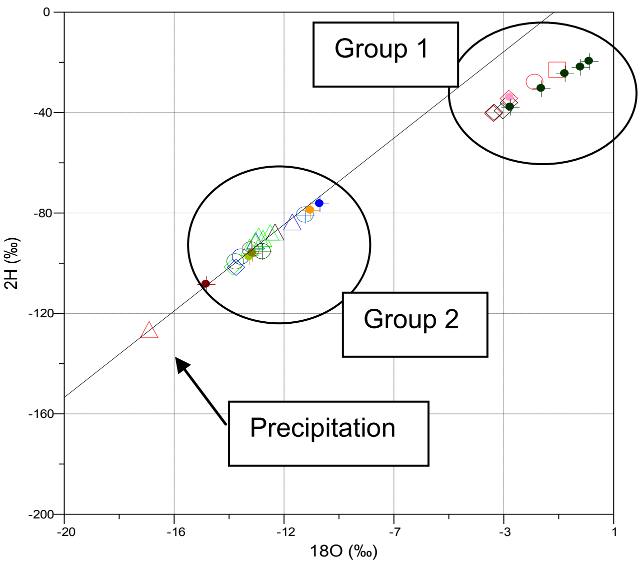

Figure 8. Isotope samples of deep ground water (Group 1), ground water connected to the annual water cycle (Group 2) and precipitation. Note that the Group 2 samples and the precipitation sample plot along the GMWL.

It is likely at mines such as the case study, that surface water storage facilities, local natural water bodies, deep ground water, and meteoric water will all have very different δ^{18}O and δ^{2}H isotope signatures. However, the base flow isotopic signature of water entering mine developments will likely be relatively constant year round. The base flow isotopic signature will be a function of the contributing flows received from surface water sources and deep ground water sources as well as the individual isotopic signature of each source. Deep ground water sources will be "enriched" such as Group 1 of Figure 8 due to rock-water interaction and geothermal exchange as discussed in Clark and Fritz (1997).

Natural water bodies will be more depleted, as in Group 2 of Figure 8. A surface water impoundment that holds water discharged from the mine, such as at the case study mine, may be isotopically enriched due to a large amount of evaporation that occurs within the mine due to the geothermal heat as well as the mine ventilation system. There may be some seasonal variation if a surface water storage facility is drained in the winter or a natural stream is ephemeral. The seasonal fluctuation of the isotopic signature will be a function of the permeability of the flow paths and the availablity of water. In the case of the issue under study in this paper, the base flow isotopic signature will be significantly disrupted when a rainfall or snowmelt event occurs. Figure 9 presents the results of several ground water samples that were collected from a pump well (07a) screened in a deep, low permeability, slow moving ground water system during a pump test on Vancouver Island, British Columbia. The volume of water removed from the well at each sample collection time is also plotted and varied from 4.6 to 29.0 m^{3}. The 07a data are also shown in Group 1 of Figure 8. Note the data plots in a logical progression with time. As pumping proceeds, the isotope signature moves away from the Group 2 surface water shown in Figure 8. A conclusion can therefore be drawn with the isotope data that the source of the deep ground water is not hydraulically connected with the shallow ground water of Group 2 shown in Figure 8.

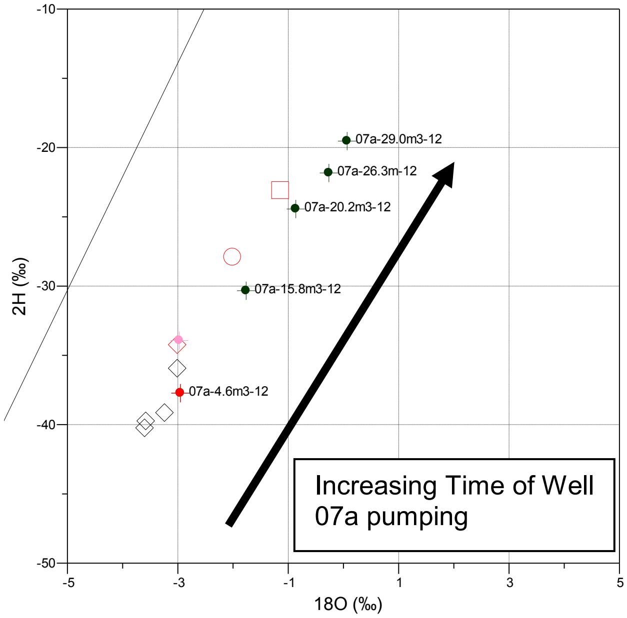

Figure 9. Well-07a pump test ground water sample isotope data showing how the signature changed with time during a pump test. Note the GMWL is located in far upper-left of the plot.

Sampling of natural water bodies and mine site water storage facilities is necessary to characterize the water that represents the shallow ground water component. Care must be taken to properly characterize the isotope signature of this surface water as it will likely vary seasonally. Water bodies that are ice covered for part of the year require the use of nonsteady isotope balance methods as discussed in Gibson (2002).

Sampling of a spring snowmelt may be the most logical event to sample at mine sites that accumulate snow, for the following reasons:

- the spring melt is typically the largest precipitation input each year,
- the timing of the spring melt is more predictable than a high intensity rainstorm or several days of extended rainfall,
- a slug of melt water entering the pit will provide a large volume of water with a relatively constant δ^{18}O and δ^{2}H signature compared with rainstorms that can have variable isotopic signatures, and
- pre-precipitation event sampling late in the winter after there has been no input (for a few months) to the hydrologic system would provide the best base flow condition characterization of an operating mine.

However, the snow must be accessible for sampling, either in the frozen state or as the snow melts and infiltrates to the subsurface. At the case study site it would be difficult to obtain samples of either snow or melt water from the pit floor due to accessibility issues. There may however be some areas that could be accessed to obtain representative samples of the input to the hydrologic system under study. An issue with conducting sampling during the spring freshet is that the snow pack will not all melt at once and will occur over several days or weeks. Another consideration is the base flow isotope signature of water entering the mine under study. Ideally, the isotope signature of the precipitation event entering the mine should be as different as possible from the base flow areas of interest.

Stadnyk *et al*. (2005) discuss an isotope method for separating ground water and recent precipitation volumes in a river utilizing ^{18}O and ^{2}H data. The paper discusses that the values of δ^{18}O and δ^{2}H can be used to estimate the input of precipitation, in the form of rainfall or snowmelt, as the new precipitation is usually isotopically different than the water already in the river. The paper also includes interpretation of snowmelt data and is a useful reference for the issue discussed in this paper.

5.2 Artificial Tracers

Artificial tracer studies also appear to be a useful tool to study the issue under discussion in this paper. Some artificial tracers have the advantage of the investigator being able to inject a known mass of tracer to a system and to measure the mass of tracer leaving the system. A tracer must be selected that will not be adsorbed by the medium it passes through or chemically react with the medium. Care must be taken to ensure there is sufficient mass of tracer added to the system so it can be detected on the discharge end. It would appear advisable to initially conduct small scale tracer tests to test theory, field methodology and equipment limitations.

A discussion of artificial tracers and their use in mine hydrology studies is provided in Wolkersdorfer (2008). This includes the different objectives and aims of mine water tracer tests as well as a discussion regarding several different types of artificial tracers. Use of an artificial tracer may require regulator approval and interpretation of the measured data may be much different depending on if the flow has been through a porous, fractured, karst or mine (underground developments) as discussed by Wolkersdorfer (2008).

Artificial tracers, with varying physical properties, can be selected and the required mass input to the hydrologic system. These artificial tracers can be added as a slug or at a constant rate for a specified period of time, depending on the goals of the study. Injection of an artificial tracer at a source and monitoring for the tracer within the mine can provide flow rate as well as time of travel information.

6 DISCUSSION AND CONCLUSIONS

Calculation of an annual water balance over a five year period, using a consistent method, resulted in no trend of increasing apparent storage within the case study mine.

The water balance was determined to be a worthwhile exercise to better understand the magnitude of inflows and outflows to the hydrologic system. However, no firm conclusions regarding storage of water within the mine could be drawn using this approach. In addition, the water balance provided information for the entire mine and no conclusions could be formed regarding the storage of water at individual mine developments. The water balance of a mine is a worthwhile analysis for the interpretation of other assessment methods.

Mine water discharge recession analysis after a large precipitation event provides useful data to evaluate how a large quantity of water moves through the mine's hydrologic system. However, no conclusions can be drawn from the information regarding the temporary storage of water at individual mine developments. The recession analysis is however useful information for the planning of a tracer study field program. Recession analysis of inflow from individual mine developments, subject to surface water inflow, has been used by other researchers (Walton-Day and Poeter, 2009) and may prove useful at other mines.

The annual mine water discharge BFI determined for five years of data at the case study mine resulted in BFI values associated with high permeability geologic catchments. However, as with the mine water discharge recession approach, no conclusions can be drawn from the total mine water discharge BFI values for the storage of water at individual mine developments.

Monitoring of water flow rates and quality from individual inactive mine developments and sumps accepting water from inactive developments, appears to be a promising approach to the assessment of water storage in discrete areas. Measurement of flows and water quality from open drillholes, or ground water pressure in shut-in drillholes also appears to be a promising approach to the assessment of the issue in local areas.

Both natural isotope and artificial tracer studies appear useful for the analysis of the type of situation discussed in this paper. However, extreme care must be taken in the planning and interpretation of any field studies.

It may not be possible to differentiate between the effects of backfill material and low permeability rock in inaccessible slow draining mine workings using hydrograph recession, water quality and tracers. However, the identification of these mine workings allows further assessment in the form of drillholes or mitigation of the movement of materials through the construction of bulkheads.

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