

INTERNATIONAL GROUNDWATER SYMPOSIUM
ON
HYDROGEOLOGY OF COLD AND TEMPERATE CLIMATES
AND
HYDROGEOLOGY OF MINERALIZED ZONES

P R O C E E D I N G S

Editor: C.L. Lin

Halifax, Nova Scotia, Canada
May 1-5, 1988

Sponsored by
ATLANTIC CANADA REGION

The International Association of Hydrogeologists
Canadian National Chapter



GROUNDWATER CONTAMINATION FROM PRECIOUS-METAL, BASE-METAL,
URANIUM, PHOSPHATE, AND POTASH (KCl) MINING OPERATIONS

Kevin A. Morin

Canect Environmental Control Technologies Ltd.
Suite 600, 1281 West Georgia Street,
Vancouver, British Columbia V6E 3J7 Canada

Paper presented at the International Groundwater Symposium of
the International Association of Hydrogeologists, Canadian National
Chapter, Atlantic Region, Halifax, Nova Scotia, May 1-5, 1988

GROUNDWATER CONTAMINATION FROM PRECIOUS-METAL, BASE-METAL,
URANIUM, PHOSPHATE, AND POTASH (KCl) MINING OPERATIONS

Kevin A. Morin
Canect Environmental Control Technologies Ltd.
Suite 600, 1281 West Georgia Street,
Vancouver, British Columbia V6E 3J7
Canada

ABSTRACT

Mining operations have five primary, interrelated environmental components which can influence water quality: the mine, waste-rock/spoils/overburden dumps, ore stockpiles, the mill, and tailings. The quality of water issuing from the components is the result of input water quality and of physical and chemical processes which operate within the components to varying degrees. These processes can be grouped under four main headings: climate, geology, chemistry of solids, and processing/handling. Degradation of water quality can occur in both surface water and groundwater leaving a component. However, surface water is more easily monitored and controlled and, thus, groundwater often represents the more critical pathway for contamination of surrounding natural waters.

Groundwater seepage from surface tailings impoundments has received significant emphasis relative to seepage from other components because of the commonly high geochemical reactivity of tailings solids and because of the toxic leach chemicals often found in mill processing waste liquids which are discarded with the solids. In order to foster consistent understanding and regulation, the mechanisms that determine water quality must be understood on a generalized conceptual basis rather than on a site-specific basis. Instead of the presentation of case studies of groundwater seepage to accomplish this goal, conceptual models that are applicable to most surface impoundments are presented. From the perspective of physical hydrogeology, the physical conceptual model indicates tailings impoundments are complex recharge areas through which tailings seepage enters underlying natural flow systems. From the perspective of chemical hydrogeology, there are two fundamental types of tailings: non-metal and metal. Non-metal tailings commonly contain a high proportion of soluble, fast-reacting minerals and groundwater seepage from these tailings often have elevated concentrations of low-toxicity species such as sodium, potassium, calcium, chloride, sulfate, and phosphate. Potash and phosphate tailings are examples of non-metal tailings. Metal tailings commonly contain a low proportion of soluble, fast-reacting minerals and groundwater seepage from these tailings can be divided into acidic, pH-neutral, and alkaline seepages. The chemical conceptual models for acidic and alkaline seepages account for pH neutralization and contaminant attenuation with increasing movement along a flowpath. The conceptual model for pH-neutral seepage is a subset of the acidic or alkaline models. Superimposed on the models are unique characteristics of a tailings pile such as cyanide from gold tailings and radionuclides from uranium tailings.

1. INTRODUCTION

Mining is a fundamental industry providing much of the raw supply of metals and non-metals for the advancement of civilization. In this context, mining enjoys a well-recognized importance, particularly in countries such as Canada where mining represents a large portion of national production. In the past, mining was considered of sufficient importance to legally dismiss responsibility for environmental and health impacts (Vranesh, 1979). The increasing concern for environmental protection, however, has tempered past attitudes and environmental protection is becoming recognized as a standard operating cost rather than an occasional problem or liability.

Mining operations are capable of degrading the quality of nearby water, air, soil, and biologic activity. As a result, the study of mining impacts on the environment is a multidisciplinary endeavor. This paper however only addresses the impacts on the quality of water. Surface-water contamination is more easily observed, controlled, and corrected than groundwater contamination and, thus, groundwater often represents the more critical pathway of water contamination from mining operations.

The delineation of impacts on groundwater by mining operations is centered around the environmental water balance of the operations (Figure 1). The schematic diagram of Figure 1 identifies five primary environmental components of mining operations: mine, waste-rock/spoils/overburden dumps, ore-rock stockpiles, mill, and tailings. Tailings represent mill-processing waste containing (1) ore solids which are often ground to a fine grain size and processed with added chemicals, (2) solid chemical precipitants and excess added chemicals from the mill process, and (3) water with dissolved solids derived from the ore rock and added chemicals. The schematic diagram is general in nature and represents most types of mining, which differ only in the existence or overlap of the five components. Most base-metal mines explicitly have all five components. For coal mines, there is no associated "mill" and "tailings" if the coal is shipped to a distant customer and the ash is not returned to the mine. Additionally, river-bed placer mining for gold and saline-lake dredging for NaSO₄ combine the mine, the spoils dump, and the tailings impoundment into one component as a result of the dredge (the mill) excavating sediment at the head of the dredge, processing the ore on the dredge, and re-depositing the spoils and processing waste behind the dredge in the river or lake.

Figure 1 highlights the solid/liquid inputs to and outputs from each primary component. Because groundwater seepages are often outputs, the quantity and quality of the seepages are dependent on all inputs to, and on processes operating within, the components. This paper initially discusses the impacts of each component on its groundwater seepage and then focusses on conceptual models of groundwater impacts from many types of surface tailings impoundments with particular reference to precious-metal, base-metal, uranium, phosphate, and potash (KCl) mining operations.

2. PRIMARY ENVIRONMENTAL COMPONENTS OF MINING OPERATIONS

A major input of water into many of the environmental components is represented by the general term, climate (Figure 1), which includes processes such as precipitation and evaporation. Climate is not a design choice for a mining operation, but simply a function of the mine location. Other inputs of water into a component are the result of interactions among the other environmental components as summarized by Figure 1.

Once water enters a component, it is affected by processes operating within the component. These processes can be gathered under three general headings: geology, chemistry of solids, and processing/handling. Geology includes stratigraphy, hydraulic conductivity, porosity, and geomorphological features such as surface slopes and runoff, which determine the direction and rate of water movement within a component. Chemistry of solids includes the presence and quantity of minerals and the solid-liquid chemical interactions which determine the change in the quality of the water passing through a component. Processing/handling represents the artificial modifications of geology and solids chemistry.

2.1 Mine

Environmental impacts of mining operations begin with the mine from which material is removed. Most operations can be placed into one of three classes: pit, underground, and dredging. Except for underground mining, climate represents a direct input of dilute water to the mine component.

Because many mines remove water as well as rock, the mine component often draws surrounding native groundwater into the operation (McWhorter, 1981). The quantity and quality of this groundwater, which is ultimately derived from climate and regulated by the geology and solids chemistry of the undisturbed subsurface, is altered by processing/handling which includes permeability enhancement around the perimeter of the excavation, availability of oxygen and other gases within the excavation, and leaching of non-native chemicals such as nitrogen-based nutrients where explosives are employed. For environmental protection, there is a trend towards diverting contaminated mine water to the mill or to a treatment system rather than release to the uncontrolled environment (Figure 1). With dredging operations, however, mine water is often not pumped from the mine site where the site is a lake or river.

2.2 Waste-rock/Spoils/Overburden Dumps

Rock or sediment from the mine component is directed to waste-rock (common terminology in hard-rock mines), spoils (common terminology in coal mining), and overburden dumps whenever the material is barren of the targeted element(s) or whenever the material contains the targeted element(s) at uneconomical concentrations. Because processing/handling of this material represents only an expense to the mining operations, the material is usually disposed of as quickly and as cheaply as possible, often in piles on the land surface in the vicinity of the mine.

In surface piles, climate provides the input of water to the component. Under gravity drainage, any net infiltration moves downward through the piles (Wardwell et al., 1982) and its quality is altered by solid-liquid interactions with the material. The nature of the solid-

liquid interactions is determined by the solids chemistry and is modified by the processing/handling which has broken up the subsurface strata and has exposed the disturbed material to accelerated weathering at the earth's surface. The downward moving water leaves the base of the pile as groundwater seepage and as surface-water flow originating at springs.

Nolan, Davis, and Associates (1987) carried out a detailed review of acid-generating waste rock in Canada limited to base-metal mines. This review identified roughly 315 million tonnes of acid-generating waste rock at 56 base-metal mines; however, only two of the Canadian provinces considered the waste rock to be a greater environmental concern than acid-generating tailings.

2.3 Ore Stockpiles

The solid material containing economical levels of the targeted element(s) (the ore) removed from the mine is sometimes sent to an ore stockpile prior to proceeding to the mill. Because this material contains the profit for the operation, it is handled and piled more carefully than waste rock. Nevertheless, once piled, it is environmentally similar to a waste-rock/spoils dump. The difference, however, lies in the intention that an ore stockpile is a short-term, temporary component of the operation, although some abandoned mines have contaminating ore stockpiles on-site.

2.4 Mill

The mill component represents the part of the mining operation that removes the targeted element(s) from the ore. Consequently, the mill is as unique as the geology, the solids chemistry, and the targeted element(s) of each mine. Nevertheless, the following general observations can be made.

The mill often represents a spatially small part of a mining operation. However, because a mill contains storage areas for processing chemicals, such as cyanide for gold milling and sulfuric acid for uranium and phosphate milling, a mill can produce a serious environmental impact whenever a spill or leak occurs. Although spills and leaks cannot usually be predicted, the number of such accidents can be minimized with good housekeeping procedures. Furthermore, such procedures also minimize contamination of runoff from the mill area.

Because the mill is a constructed facility, climate does not directly provide an input of water to it, but determines natural runoff from the mill area. Any water required by the mill is drawn from a fresh-water supply and from other components (Figure 1). Geology has only a minor direct importance for the physical structure of a mill, but it determines the amount of preprocessing such as grinding required by the ore. The solids chemistry of the ore is fed into the mill and the processing/handling, which represents the physical and/or chemical nature of the mill circuit, removes the targeted element(s). The waste products from the circuit include the processed ore solids, solids from any chemical precipitants and unused added chemicals, and dissolved solids from the added chemicals and the ore material.

2.5 Tailings

The tailings solids and liquid discharged from the mill can be

directed to several destinations (Figure 1). Discharge to the uncontrolled environment has been practiced in the past with detrimental consequences (e.g., Cherry et al., 1986), but is now discouraged except where environmental testing indicates there will likely be no serious degradation of the environment. In this context, the disposal of tailings into lakes is receiving increased attention. Similarly, the discharge of tailings into the mine is also receiving increased attention for control of environmental impact and water movement, although placement of tailings in a mine during active operation can complicate the operation. More commonly, tailings are discharged into surface impoundments (e.g., Morin, 1988, these proceedings). The U.S. Environmental Protection Agency has estimated that there are over 24000 tailings impoundments in the U.S.A alone.

For the construction of surface impoundments, the local geology is examined for an acceptable site, often in a low-elevation area such as a valley or basin where natural walls will provide a portion of the impoundment dam. A lowland impoundment site may be a groundwater discharge zone, a recharge zone, or a complex combination of discharge and recharge, which changes as the water level in the impoundment rises. If a highland site is chosen, the impoundment will likely be a recharge zone. In any case, during operation, tailings impoundments commonly have a sufficient water level from climate and mill discharge to provide net recharge through seepage to the underlying natural groundwater flow system. The quality of this seepage is determined by the quality of the tailings liquid and the solids chemistry of the tailings solids.

3. GROUNDWATER CONTAMINATION FROM SURFACE TAILINGS IMPOUNDMENTS

The previous sections have discussed the primary environmental components of mining operations. Although all the components can cause degradation of the environment, tailings impoundments have traditionally received the most attention because of the typically high geochemical reactivity of tailings and their disequilibrium from local natural conditions. The high geochemical reactivity relative to other components is the result of the commonly fine grain size of the tailings solids and the commonly strong leach chemicals in the tailings liquid. The disequilibrium from the natural environment is the result of the mill circuit that includes such processes as grinding, heating, and addition of strong leach chemicals during the relatively short residence time (usually less than 2 days) in the circuit. The high reactivity and the disequilibrium provide the opportunity for strong, rapid degradation of water quality in and around the impoundment as the tailings evolve towards equilibrium with the natural environment. Because surface water is easily observed and controlled, the release of contaminated surface water directly to the uncontrolled environment (Figure 1) can be minimized. On the other hand, groundwater seepage is not as easily observed and not as easily controlled if the impoundment is not initially designed and built for seepage control. Consequently, groundwater can often be the critical water pathway for interaction with the surrounding environment and can ultimately be a relatively expensive pathway to regulate.

Groundwater contamination by surface impoundments can be divided into

two parts. Firstly, physical hydrogeology determines the direction and rate of groundwater movement through the tailings pile and into the surrounding natural flow system. The physical hydrogeology of an impoundment is a function of the geology, climate, and processing/handling as explained in previous sections. Secondly, chemical hydrogeology addresses the changes in aqueous chemistry along the groundwater flowpaths. The chemical hydrogeology of a tailings impoundment is a function of solids chemistry and processing/handling in the mill and impoundment. Whereas one conceptual model can be created to generally describe the physical hydrogeology of many types of surface tailings impoundments, a conceptual model for chemical hydrogeology is dependent on the mill circuit employed at a mine which in turn is dependent on the factors discussed in Section 2.4. The following sections present the generalized physical conceptual model then discuss chemical conceptual models for precious-metal, base-metal, uranium, phosphate, and potash (KCl) tailings.

3.1 Conceptual Model For Physical Hydrogeology

Morin (1988, these proceedings) defines a conceptual model for the physical hydrogeology of uranium-tailings impoundments. This model is, in fact, valid for most surface impoundments.

Tailings are typically contained by man-made impoundment dams and/or natural walls (Stratum B, Figure 2). In some cases, the tailings are underlain by a local low-permeability stratum such as natural peat or man-placed clay (Stratum C). In other cases, there is no Stratum C and tailings lie directly over a more extensive Stratum D. Stratum D may be sufficiently thick to render deeper strata relatively unimportant from a tailings seepage perspective.

Because tailings are often discharged to an impoundment as a slurry with more than 50% water, tailings piles often provide net recharge to the underlying groundwater system. Additionally, recharge of surface water in surrounding watercourses occurs through (1) seepage through the embankments, (2) tailings seepage in Stratum D (Figure 2) discharging upwards into the watercourses, and (3) direct runoff from the pile which is usually prevented in modern impoundments because of frequent contamination.

In moist climates, tailings piles can be expected to form a water-table mound on a relatively shallow water table. In drier climates, a thick unsaturated zone can be initially expected beneath the pile so that a perched water table exists in the pile. Depending on seepage rates and other conditions, the unsaturated zone may become saturated and a water-table mound would then exist.

Groundwater movement within a tailings impoundment itself can be expected to be complex. The embankments and underlying strata may have hydraulic conductivities that are significantly different from those within the tailings pile. Additionally, tailings are typically discharged into an impoundment through a pipe at one corner or along one side of the impoundment, allowing preferential accumulation of coarse particles and high-density minerals near the pipe. As fluctuations in discharge rate, ore mineralogy, and mill processing occur, the lateral boundaries between sand, silt, and clay and between preferential accumulations of minerals migrate laterally as the pile grows vertically. As a result, irregular

deltaic facies with interfingering of high and low permeability layers develop. Consequently, a significant horizontal component of groundwater flow and a significant variable vertical seepage rate across the impoundment can arise. Furthermore, when a large percentage of the tailings pile is highly soluble in water such as NaCl in potash tailings, solution caverns can form to further complicate groundwater flow.

In summary, the physical conceptual model indicates a net seepage out of an impoundment is usually expected. However, the lateral and vertical variability in a tailings pile and its embankments indicate that a reliable definition of seepage flow directions and rates requires detailed monitoring across the impoundment and through its thickness.

3.2 Conceptual Models For Chemical Hydrogeology

From a chemical viewpoint, tailings solids are composed of minerals that are soluble in water. From an environmental viewpoint, many of the minerals comprising the solids dissolve very slowly so that they have a negligible impact on water quality and can thus be considered as essentially stable. Consequently, only the surfaces of these stable minerals are environmentally important through their ability to exchange ions with the liquid phase.

There are also fast-reacting ("reactive") minerals in tailings solids, comprising a negligible percentage up to essentially all of the solids depending on the type of tailings. This reactive portion primarily determines the water quality in the tailings seepage. From this perspective, two general types of tailings can be defined: non-metal and metal. This classification based on the reactive fraction of tailings solids is derived from common mining terminology, but is strictly incorrect chemically because metals such as calcium usually occur in all types of tailings. The classification generally coincides with groupings based on (1) metal toxicity in which metals that are toxic only at high concentrations (greater than several mg/L) are found in both non-metal and metal tailings whereas metals that are toxic in low concentrations (less than a few mg/L) are mostly limited to metal tailings and (2) the percentage of tailings solids that is readily soluble and reactive is typically high in non-metal tailings and typically low in metal tailings.

3.2.1 Non-metal tailings

This type of tailings is often characterized by a high soluble fraction, which in some cases is the result of mining of evaporative beds such as NaCl and KCl. Although a suite of chemical conceptual models can be developed to consistently describe metal tailings from many types of mining operations (Section 3.2.2), chemical models for non-metal tailings must be developed specifically for each type of mining. The two non-metal models discussed in this paper are applicable to potash tailings which are found in several countries such as Canada (particularly Saskatchewan), the United States of America (particularly New Mexico), and the Union of Soviet Socialist Republics, and to phosphate tailings found in countries such as South Africa and the United States of America (notably in Florida). Although the term, "potash", can refer to many potassium minerals, it is used in this paper to indicate KCl.

Potash mining involves preferential mining of KCl-rich beds from

evaporative sequences in the subsurface for the creation of fertilizer. Mill processing varies among mines and can employ such techniques as recrystallization, flotation, and electrostatic separation (McKercher, 1983). The tailings solids from the mill usually contain NaCl with smaller percentages of KCl, relatively slow-reacting minerals such as quartz, feldspars, and carnallite ($KMgCl_3 \cdot 6H_2O$), and clay minerals such as illite which are referred to as "slimes". The tailings liquid usually contains sodium and chloride above 100,000 mg/L, potassium at a few tens of thousands of mg/L, and other elements at much lower concentrations. Occasionally sulfate and calcium are at elevated concentrations because of gypsum dissolution. In cases where organic chemicals are added in the mill process, such as glycol solutions for flotation, these chemicals will be present in the tailings slurry; however, this concern is rarely recognized in environmental monitoring.

Because NaCl and KCl are soluble in precipitation falling on the tailings and because tailings liquid is a concentrated Na-K-Cl brine, groundwater seepage from potash tailings impoundments is easily recognized through elevated concentrations of sodium, potassium, and chloride. However, natural groundwater at mining sites in Saskatchewan and New Mexico often contain elevated levels of sodium, calcium, sulfate, and chloride (e.g., Morin, 1987; Nelson, 1983) and, thus, early detection of tailings seepage against this background groundwater is not often possible. Furthermore, the high production rate of potash tailings such as 3 000 000 tonnes annually at some mines (Hart, 1985A) represents a heavy loading on underlying sediments which produces upward movement of natural groundwater into the base of the tailings pile during consolidation (van der Kamp and Maathuis, 1985) and thus limits seepage from the pile. As a result, the time at which the upward movement becomes negligible and tailings porewater can begin to seep from the impoundment cannot be known without detailed hydrogeologic monitoring beneath the impoundment. Despite this ambiguity on initiation and early detection of seepage exists, long-term seepage into the subsurface is easily recognized as concentrations of sodium, potassium, and chloride in groundwater increase by tens of thousands of mg/L.

The chemical conceptual model for potash tailings seepage indicates the subsurface migration of this brine is not hampered or regulated by the geochemical mechanisms of mineral precipitation or co-precipitation because of the high solubility of chloride minerals. On the leading edge of the brine plume, ion exchange creates a chromatographic effect in water chemistry where chloride essentially travels unretarded with the groundwater and arrives first at a point in the flow system, sodium is slightly retarded behind chloride because of exchange for calcium, magnesium, etc., and potassium is retarded behind sodium because of its stronger affinity for exchange sites and clay lattices (Cameron, 1981; Morin, 1987). Within the body of the brine plume, ion exchange is unimportant because the leading edge of the plume has already initiated most of the exchange and because aqueous concentrations far exceed the number of exchange sites on most sediments. Consequently, natural regulation of brine plumes from potash tailings depends primarily on the physico-chemical process of dispersion (dilution). There is, however, some evidence that denser plumes may behave as an independent aqueous phase, sinking to the bottom of an aquifer and then migrating down-elevation possibly opposite to groundwater flow (e.g., Morin, 1987). In this case,

dispersion is negligible.

For reclamation and decommissioning, the most promising approach is deep-well injection of the tailings liquid and the dissolved tailings solids because the brine "disappears" for a long period of time. However, deep-well injection can be costly because of the depth and number of required wells and the volume of tailings that must be directed into the wells. Alternative options of mine backfill and hydraulic isolation through surface capping have been examined (Hart, 1985B).

Phosphate mining usually involves pit mining of phosphate-rich clayey material for the production of fertilizer. In order to produce orthophosphoric acid from the ore, mill processing usually combines sulfuric acid with the ore. Tailings solids from this processing are predominately composed of gypsum containing significant quantities of phosphate ("phosphogypsum") and often fluoride. Tailings liquid, for cases where the acid is not neutralized after processing, is typically at pH values below 3 with several thousands of mg/L of sulfate and at least hundreds of mg/L of phosphate. When the acid is neutralized by lime after processing, sulfate is at concentrations of several hundreds of mg/L and phosphate is at concentrations of a few tens of mg/L (Wrench, 1986).

The chemical conceptual model for phosphate tailings seepage indicates mineral precipitation is important, unlike for potash tailings seepage, because of the lower solubilities of sulfate and phosphate minerals. In acidic seepage from unneutralized tailings, the dissolution of natural calcium carbonate minerals (calcite, dolomite, etc.) in the groundwater system to neutralize pH will produce significant quantities of aqueous calcium which then precipitate as gypsum. This geochemical scenario is also part of attenuation of acidic seepage from metal tailings (Section 3.2.2). Neutralization of the pH in the groundwater system can also be expected to result in phosphate mineral precipitation. In seepage from neutralized tailings, gypsum may precipitate whenever the elevated sulfate concentrations mix with background groundwater with relatively high calcium concentrations, although the quantity of precipitate will be significantly less than the amount produced during neutralization of acidic seepage in the groundwater system. Phosphate may also precipitate from seepage from neutralized tailings depending on background water chemistry.

For reclamation, the inactive surfaces of phosphate-tailings piles undergo secondary recrystallization which reduces infiltration and increases runoff. Additionally, the neutralized tailings produce an environment favorable for growth of vegetation (Wrench, 1986) to reduce infiltration into the tailings, although topsoil addition on the surfaces reportedly provides better control of species composition (Erwin et al., 1985). Consequently, reclamation of phosphate tailings appears to be less difficult and less costly than for many other types of tailings.

3.2.2. Metal Tailings

Metal tailings typically contain a relatively low proportion of reactive minerals and yet are capable of producing relatively high levels of toxic metals in tailings porewater. These metals include zinc, nickel, mercury, and iron.

Because the aqueous behavior of many metals are pH sensitive, metal tailings can be divided into three subtypes: acidic, pH-neutral, and alkaline tailings. Seepages from these tailings initially reflect the pH subtype of the tailings; however, because most natural environments are pH-neutral, the acidic and alkaline seepages eventually approach neutral pH along their flowpaths (Figure 3) as a result of solid-liquid interactions and/or dispersion. The geochemical reactions that occur during neutralization and, in effect, mediate the rate of neutralization comprise the chemical conceptual models for acidic and alkaline seepages. The pH-neutral seepages do not have a distinct conceptual model and are accounted for by portions of the acid or alkaline models that describe geochemical reactions occurring as neutralization approaches completion. Superimposed on these models are the unique environmental problems of each tailings impoundment such as cyanide from gold tailings and radionuclides from uranium tailings.

The most recognized and, thus, the most studied type of seepage from mining operations is acidic in nature and is commonly referred to as "acid drainage". The prevalence of acid drainage at mining operations is apparent in published literature. For example, Ferguson and Mehling (1986) estimated that 30% of operating metal mines in British Columbia, Canada, were producing acid drainage.

Many of the detailed studies on tailings seepage have taken place at uranium-tailings impoundments because of the extremely toxic nature of some radionuclides. However, seepage from uranium tailings is similar to seepage from base-metal and precious-metal tailings except for the additional concern over radionuclides. Based on studies of acidic uranium-tailings seepage, a chemical non-radionuclide-specific conceptual model has been developed to describe the neutralization of the acidic seepage which is therefore applicable to many types of tailings, to the other mine components, and to acid drainage in general (Morin et al., accepted A; Morin, 1988, these proceedings).

The chemical conceptual model for acidic seepage begins with acidic porewater in the tailings pile either from direct discharge of acidic tailings liquid from the mill or from oxidation of sulfide minerals in the solids. The low-pH conditions increase the solubility of reactive minerals as well as cause desorption of contaminants from non-reactive minerals. Within the tailings pile or in the underlying natural groundwater flow system, the acidic seepage eventually encounters calcium carbonate minerals. The subsequent dissolution of calcium carbonate minerals neutralizes pH and may initiate the precipitation of siderite and Al-OH minerals, may cause the co-precipitation or adsorption of other aqueous species, and, in addition to the increase in aqueous calcium, may lead to gypsum precipitation. After the calcium carbonate minerals are completely dissolved, acidic seepage causes the dissolution of the precipitated minerals which provides some degree of pH neutralization. In this way, a theoretical step-function increase in pH occurs along a flowpath as schematically depicted in Figure 3 and discussed in more detail in Morin (1988).

Seepage from metal tailings at neutral pH are reportedly in equilibrium with minerals such as gypsum, Al-OH minerals, and calcite

(e.g., Morin, 1988) because neutralization is occurring within the tailings pile or neutralization occurs in the mill circuit after acidic or alkaline processing. Consequently, pH-neutral seepage is a subset of the acid or alkaline models.

The conceptual model for alkaline seepage is not as well defined as the acid model because of the lesser public concern. The alkaline model begins with discharge of unneutralized alkaline tailings slurries to impoundments from mills with strongly alkaline circuits such as found in alkaline-leach uranium processing and bauxite (aluminum) processing. Alkaline processing usually leaches the target element(s) through formation of OH^- or CO_3^{2-} aqueous complexes, which also leaches other metals from the ore. The tailings liquid therefore contains elevated levels of alkalinity and some metals. The tailings solids are usually composed of only a relatively small reactive content, which is often mostly O-OH minerals such as lime and carbonate minerals such as calcite. Within an impoundment, the presence of O-OH minerals can create strongly alkaline porewaters above pH 9 for many years. However, in high carbonate waters, these minerals either are eventually converted to carbonate minerals or dissolve and cause the precipitation of carbonate minerals, which produce more-natural pH values of 7-9. Until the conversion is complete, groundwater seepage at $\text{pH} > 9$ enters the underlying groundwater flow system, carrying elevated levels of some metals and possibly mobilizing more metals from the natural sediment. The dissolution of metals from sediment can aid in pH neutralization through the formation of OH^- complexes which represents a consumption of free OH^- . For example, gypsum dissolution from the formation of Ca-OH complexes and $\text{Al}(\text{OH})_3$ dissolution from the formation of $\text{Al}(\text{OH})_4^-$ complexes would contribute to neutralization. Such reactions operating along a flowpath would result in eventual neutralization as occurs in the acid model (Figure 3). Additionally, dispersion (mixing) into background groundwater would contribute to pH neutralization. The refinement of the alkaline model to the level of the acid model must await more detailed studies.

Each tailings impoundment has unique characteristics, particularly resulting from mill processing, that adds additional complexity to the conceptual models. Uranium mill processing often includes sulfuric acid leaching, resulting in high aqueous levels of metals and radionuclides within the mill circuit. For mills that do not neutralize this acid, tailings discharge initiates the acid conceptual model and elevated levels of radionuclides accompany the seepage. For mills that neutralize the acid, radionuclides chemically precipitate or co-precipitate as reactive compounds, but will redissolve if the acid model becomes applicable through processes such as sulfide-mineral oxidation. The migration of radionuclides in groundwater adds an additional facet to the acid model (Morin et al., accepted B; Morin and Cherry, 1988, these proceedings).

Gold mill processing often uses cyanide to separate the gold from the ore. Concentrations of cyanide in tailings liquid from this processing are up to several hundreds of mg/L. Because of the severe toxicity of this concentration, some mills have a subcircuit for cyanide destruction, usually employing the Inco SO_2 process or the Degussa hydrogen peroxide process. Cyanide destruction is often highly successful, lowering concentrations by roughly two orders of magnitude. However, from an

environmental viewpoint, 1 mg/L of cyanide may still be toxic. The behavior of cyanide in water is significantly pH-dependent only above pH 7, which suggests cyanide will behave similarly in acidic and pH-neutral groundwater seepage, but the elevated levels of metals in acidic seepage may stabilize high levels of cyanide due to cyanide's renowned ability to strongly form metals complexes. Detailed studies of cyanide behavior in groundwater are generally lacking, but cyanide is reportedly stable in groundwater systems for several years (e.g., Klohn Leonoff Consulting Engineers, 1984).

For reclamation, research is concentrating on limiting infiltration through and seepage out of tailings piles. As a result, several methods of capping are receiving a great deal of attention. For acidic tailings seepage originating from sulfide-mineral oxidation, research is also concentrating on methods for preventing oxygen from entering piles, which again is a type of capping, and for the addition of neutralizing materials to limit the generation of acid.

4. CONCLUSION

Mining is a well recognized industry that provides much of the metals and non-metals for human development. In spite of this importance, a mining operation is responsible for protection of the surrounding environment. One aspect of environmental protection is water quality, which should not be degraded as defined by applicable water-quality guidelines. In order to foster consistent understanding and regulation, the mechanisms operating at mines that determine water quality must be understood on a generalized conceptual basis rather than on a site-specific basis. Instead of the presentation of a number of case studies to accomplish this goal, this paper has concentrated on generalized conceptual models that are applicable to many types of mining. Although degradation of both groundwater and surface water can occur at mining operations, only groundwater is examined here because direct runoff of contaminated surface water is often controlled.

In order to conceptually examine water quality impacts of mining operations, the operations were divided into five primary components: the mine, waste-rock/spoils/overburden dumps, ore stockpiles, the mill, and tailings. The water quality issuing from these components is determined by processes collectively identified as climate, geology, chemistry of solids, and processing/handling. Emphasis is placed in this paper on surface tailings impoundments because of the widely recognized ability of tailings to rapidly and seriously degrade surrounding water quality.

From the viewpoint of physical hydrogeology, most surface impoundments represent complex groundwater recharge zones in which tailings seepage enters underlying natural flow systems. From the viewpoint of chemical hydrogeology, there are two types of tailings: non-metal and metal.

Non-metal tailings often contain a high proportion of reactive minerals, such as NaCl and gypsum. Groundwater seepages from this type of tailings often have high concentrations of low-toxicity species such as sodium, potassium, calcium, sulfate, chloride, and phosphate.

Metal tailings often contain a low proportion of reactive minerals, such as $Al(OH)_3$ and calcite. Groundwater seepages from this type of tailings can be divided into three subtypes: acidic, pH-neutral, and alkaline. Because natural environments are usually at neutral pH, the acidic and alkaline seepages which typically have high concentrations of high-toxicity metals approach neutral pH and aqueous contaminants are attenuated as the seepages travel along a flowpath. From this perspective, pH-neutral seepage is a subset of acid or alkaline conceptual models. Superimposed on these models are individual characteristics of an impoundment such as cyanide from gold tailings and radionuclides from uranium tailings.

REFERENCES

- Cameron, D.R. 1981. Brine Migration: Monitoring Evaluation. Potash Corporation of Saskatchewan Contract MB-6037.
- Cherry, J.A., F.M.M. Morel, J.V. Rouse, J.L. Schnoor, and M.G. Wolman. 1986. Hydrogeochemistry of sulfide and arsenic-rich tailings and alluvium along Whitewood Creek, South Dakota. Colorado School of Mines, Mineral and Energy Resources Series.
- Erwin, K.L., G.R. Best, W.J. Dunn, and P.M. Wallace. 1985. Marsh and forested wetland reclamation of a central Florida phosphate mine. *Wetlands*, 4, p.87-104.
- Ferguson, K.D., and P.E. Mahling. 1986. Acid Mine Drainage In British Columbia: The Problem And Search For Solutions. Environment Canada File Report; presented at the Tenth CIM District Six Meeting, October 2-4, 1986, Victoria, B.C.
- Hart, R.T. 1985A. Waste Management In The Saskatchewan Potash Industry: Two Case Histories. Energy, Mines, and Resources Canada Contract OSQ83-00247.
- Hart, R.T. 1985B. A Review Of Waste Management In The Potash Industry, And Options For Decommissioning And Abandonment Of Potash Tailings Piles. Energy, Mines, and Resources Canada Contract OSQ83-00247.
- Klohn Leonoff Consulting Engineers. 1984. Fate And Persistence Of Cyanide In Groundwater. Environment Canada Contract KE-603-3-1520.
- McKercher, R.M., ed. 1983. Potash Technology, Proceedings of the 1st International Potash Technology Conference, October 3-5, Saskatoon, Saskatchewan. Pergamon Press, Toronto.
- McWhorter, D.B. 1981. Predicting groundwater response to disturbance by mining - selected problems. IN: Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation, December 7-11, 1981, Lexington, Kentucky, p. 89-95.
- Morin, K.A. 1988. Physical and chemical hydrogeology of uranium tailings in Canada and the United States of America. International Groundwater Symposium of the International Association of Hydrogeologists, Halifax, Nova Scotia, 1988, these proceedings.
- Morin, K.A. 1987. Physical And Chemical Hydrogeology Of The IMCC K2 Potash Minesite. Technical Report, Mines Pollution Control Branch, Saskatchewan Department of Environment.
- Morin, K.A., and J.A. Cherry. 1988. Variations in natural-decay-series disequilibrium along groundwater flowpaths. International Groundwater Symposium of the International Association of Hydrogeologists, Halifax, Nova Scotia, these proceedings.
- Morin, K.A., J.A. Cherry, N.K. Dave, T.P. Lim, and A.J. Vivurka. Accepted A. Migration of acidic groundwater seepage from uranium-tailings impoundments. 1. Field study and conceptual hydrogeochemical model. Accepted for publication by the Journal of Contaminant Hydrology.
- Morin, K.A., J.A. Cherry, N.K. Dave, T.P. Lim, and A.J. Vivurka. Accepted B. Migration of acidic groundwater seepage from uranium-tailings impoundments. 2. Geochemical behavior of radionuclides in groundwater. Accepted for publication by the Journal of Contaminant Hydrology.
- Nelson, J.D. 1983. Engineering considerations in design and operation of potash tailings impoundments. IN: Potash Technology, Proceedings of the 1st International Potash Technology Conference, October 3-5, Saskatoon, Saskatchewan, edited by R.M. McKercher, p.801.
- Nolan, Davis, and Associates. 1987. Study Of Acid Waste Rock Management At Canadian Base Metal Mines. National Uranium Tailings Program Contract Report 23317-6-1738/01-SQ.
- van der Kamp, G., and H. Maathuis. 1985. Excess hydraulic head in aquitards under solid waste emplacements. IN: 17th International Congress of the International Association of Hydrogeologists, January 7-10, Tucson, Arizona.
- Vranesh, G. 1979. Mine drainage: the common enemy. IN: Mine Drainage, Proceedings of the First International Mine Drainage Symposium, Denver, Colorado, May 1979, edited by G.O. Argall and C.O. Brawner, p. 54-97.
- Wardwell, R.E., J.D. Nelson, D.B. McWhorter. 1982. Water movement in waste piles from surface mining. IN: 1982 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, December 6-10, 1982, edited by D.H. Graves, p. 71-77.
- Wrench, B.P. 1986. Surface water management and vegetation at a phosphogypsum tailings impoundment. IN: Geotechnical and Geohydrological Aspects of Waste Management, Proceedings of the 8th Annual Symposium on Geotechnical and Geohydrological Aspects of Waste Management, Fort Collins, Colorado, February 5-7, 1986, publisher: A.A. Balkema, p.173-182.

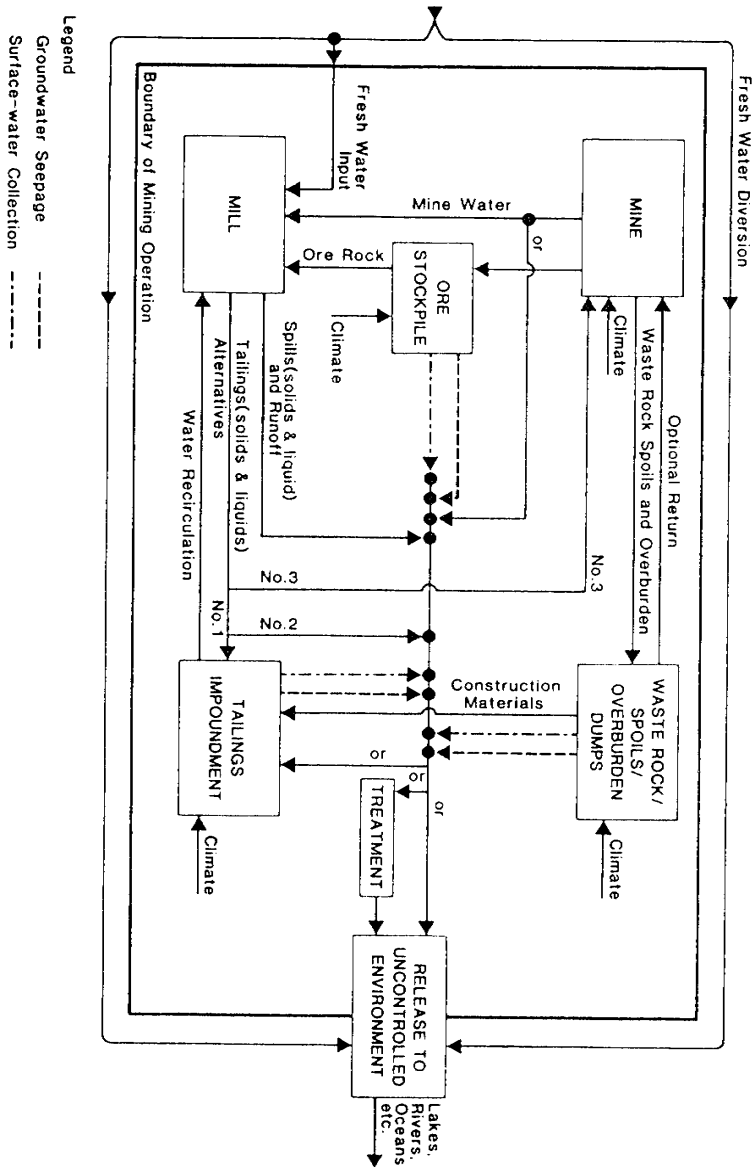
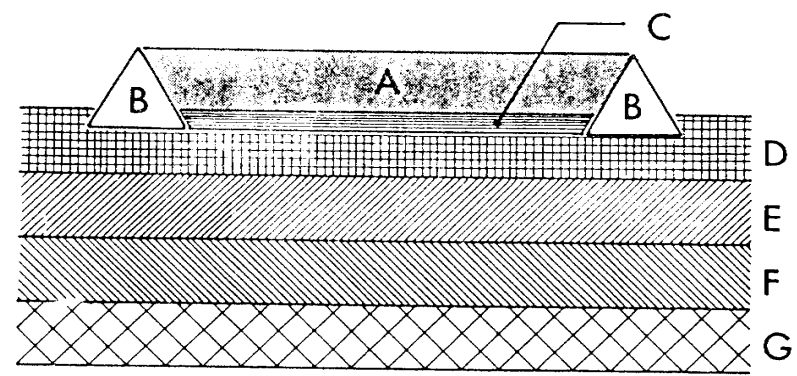


Figure 1. Schematic diagram of the water balance of a mining operation.



LEGEND:

- A — TAILINGS PILE
- B — IMPOUNDMENT OR BEDROCK WALLS
- C — LOW PERMEABILITY BASAL LAYER (not always present)
- D,E,F,G — ALTERNATING STRATA OF HIGH AND LOW PERMEABILITY

Figure 2. Schematic diagram of the conceptual model for the physical hydrogeology of surface tailings impoundments.

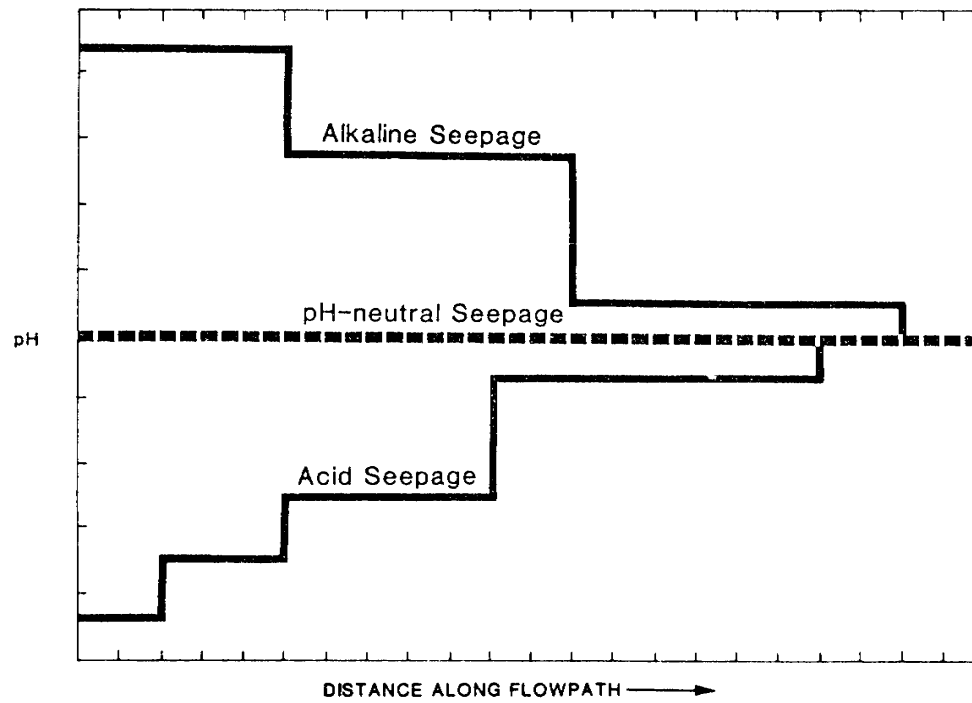


Figure 3. Schematic diagram of the conceptual models for the chemical hydrogeology of metal-tailings seepage.